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ACOUSTICAL TECHNIQUES/DESIGNS INVESTIGATED  
DURING THE SOUTHEAST ASIA CONFLICT 1966 - 1972

Jack Harris

FINAL REPORT

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21. ABSTRACT (Continue on reverse side if necessary and identify by block number) With the ending of the American military involvement in the Southeast Asia conflict of the 1960's and 1970's, it became appropriate to summarize those technical investigations which might be of reference value to future scientific workers. In particular there was an extensive amount of acoustical research done. A summary of these investigations was published in 1974 by the Department of the Navy under the title "Acquisition, Reduction, and Analysis of Acoustical Data," Library of Congress catalogue number 74-600108. Not all of		

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the useful information was reported, namely because of their highly classified nature. Since then much of that information has been downgraded and become accessible. This report completes what was not reported earlier because of classification. It summarizes the technical research by topical areas, with the sources of information being reports from government agencies supporting acoustical research efforts of the conflict. The majority of these reports are from studies of Acoustical Working Group, a committee of knowledgeable persons from civilian and government agencies responsible for performing acoustical studies relevant to the Southeast Asia conflict. Though thousands of pieces of classified literature related to acoustic, infrasonic and seismic information reported from 1966 through 1972 were researched - the period where the majority of the study efforts were done - only those documents which have some apparent usefulness in the future have been reported.

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## I N T R O D U C T I O N

Upon analysis of the reports, letters, and technical memorandums related to acoustics generated by the Southeast Asia (SEA) conflict, the information grouped itself into the areas of: (1) electronic circuit considerations for inbuoy processing related to automatic detection and/or classification; (2) the use of spectrum analyzers for detection and classification enhancement against aircraft and motorized vehicles including automatic computer classification techniques; and (3) target location information and techniques. As such, the following sections of this report describe this information following that grouping. Each section has a series of summarizing paragraphs with, as appropriate, the appendices containing excerpts from the documents from which the information was obtained. In this manner the main body of the report summarizes the technical material by topics, with the appendices giving the supporting information in more detail. In addition a complete identification of the source is contained in the main body by reference number. Only a small portion of the total information available is listed in the list of references. This in no way implies that other related efforts were not reported in similar areas, but the references best summarize the particular technologies discussed.

Through guidance given by reference 1, all Secret information contained in this report has been downgraded to Confidential, although the bibliography identification will reference the report classification as it was originally classified. Although the majority of the information used had as a source studies which were generated out of the Naval Air Development Center, Warminster, PA., data from other Naval laboratories or government laboratory sources are also summarized including some effort that took place after the SEA conflict ended in 1972. Finally similarity of certain technical aspects of the seismic effort, especially when coupled with acoustics, also justified inclusion.

All of the technical efforts reported on have as a generic beginning sponsorship from the Defense Special Projects Group (DSPG). This group was the Department of Defense's main focal point for the specialized surveillance operations of the Southeast Asia conflict. Before discussing the various technological subsets relating to the classified aspects of acoustics which were investigated and implemented during the IndoChina conflict, it is appropriate to appreciate historically the program which led to this acoustical development. Although U.S. involvement in Southeast Asia was spread over a period of time from the early 1960's until our final withdrawal in the mid 1970's, the time of particular interest for acoustical research was at the peak of its development for operational use in the late 1960's. Fortunately during late 1971, a study was done to try to summarize the technology of the DSPG efforts as it pertained to the Navy's Anti-Submarine Warfare (ASW), reference 2. In order to gain an insight historically of the total program information, this document is used to give an overview of the total system from both an historical and technical standpoint.

## HISTORICAL OVERVIEW

## GENESIS

The United States' tactical sensor systems program, like the Polaris program, is an excellent example of the rapid progress that can be achieved when an urgent need is recognized at the highest levels of government. In this case, the need was for a means of interdicting the flow of men and material in a guerrilla warfare situation. The solution resulted from the independent concern of a small group of some of the country's most distinguished physicists over the frustration and ever increasing cost of the war in Vietnam. The scientists recognized that indiscriminate technological progress might amount to no more than an enormous economic waste under the special conditions of guerrilla warfare.

Thus it happened that in January of 1964 at a meeting of the American Physical Society, M. Goldberger, who was then Chairman of the Jason problem-solving group of the Institute for Defense Analyses (IDA), asked William A. Nierenberg to head a Jason summer study on the problems of Vietnam. Working that summer at the University of California at La Jolla, the group produced the first significant paper on special warfare problems; IDA Research Paper P-170, "Working Paper on Internal Warfare." The report, which showed mostly negative results, had little impact other than educational shock to those involved. No further work was done for over a year until, at the stimulus of M. Gell-Mann\* and S. Deitchman, the Jason group decided to reopen the question of Vietnam problems with another larger summer study in 1966.\*\*

Independently, in the winter of 1965-6, a highly distinguished group of scientists had met informally on the same types of problems and had elicited strong interest from the Department of Defense in supporting a study for the coming summer. It rapidly became apparent that there was considerable overlap in membership between the two groups. It was therefore decided to merge the two summer studies and to subsume them within IDA for administrative convenience.

The 1966 summer study addressed four topics:

- Bombing effectiveness
- Reliability of data (on infiltration and body counts)
- Electronics
- Ho Chi Minh Trail barrier.

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\* The physicist noted among other things for his formulation of the "Eight-fold Way," a system for classifying subatomic particles.

\*\* In 1964, Dr. Jesse Coop of NAVAIRDEVCON proposed a silent sensor system similar to that eventually recommended by the Jason group.

The last topic resulted in the most significant study conducted up to that time, "Air-Supported Anti-Infiltration Barrier," IDA Study S-255. This report, which made several specific recommendations for solving trail interdiction and general infiltration problems, was the basis for a briefing presented to Secretary of Defense Robert A. McNamara in August 1966. The briefing was so well received that the engineering development work called for in the report was initiated immediately by creating the special tri-service task force JTF 728, then known as the Defense Communications Planning Group (DCPG).

#### DEFENSE SPECIAL PROJECTS GROUP

The powerful charter of Defense Communication Project Group, later changed to DSPG, directly reflected the magnitude of the threat posed by the Ho Chi Minh Trail. To implement the Secretary's decision with all due speed, the group was given unprecedented authority including:

- (1) direct access to the Secretary of Defense for major policy decisions,
- (2) the ability to task three Services with efforts leading to mission accomplishment,
- (3) generous funding,
- (4) complete authority over concept development, planning, system design, testing, procurement and distribution.

Most extraordinarily, DSPG was granted authority to make mistakes--necessary whenever speed is essential. The entire project was assigned a DX-01 priority--equal to that of the Polaris program.

There were two principal Phase I air emplaceable sensor types: one acoustic and the other seismic. Acoustic sensors, or "Acoubuoys," are of two types; one designed to hang up in trees and the other to implant itself in the ground. In either version, the Acoubuoy operates in three modes: impulse detection, truck detection, and both. When triggered by a detection, the Acoubuoy transmits an identifying code plus the next 10 seconds of audio signal being received.

The triggering logic differs according to mode. In the impulse mode any sudden sound that exceeds a certain threshold is sufficient for triggering. "Button bomblets" or BB's--small firecracker-like devices that detonate when stepped on--were proposed for use with sensors in this mode. BB's were ultimately deemed impractical and never deployed; in fact, the sensors themselves were never used in the impulse mode.

In the truck detection mode, the sensors employ a variable threshold to accommodate the varying level of background noise. They trigger only when a continuous sound source, such as a truck, increases in loudness more rapidly than the automatic gain control can accommodate. In field use, the detection range against trucks under good conditions is 300 meters. Unfortunately, the Phase I Acoubuoy was plagued with the problem of high false alarms from such sources as artillery, planes, rain, animals, thunderstorms, etc.; a considerable amount of subsequent work was addressed to solving this problem.

The seismic sensors, always ground-implemented, are sensitive to much lower frequencies than the acoustic sensors and have proven more valuable in the field. Seismic sensors, when triggered, simply transmit their identifying codes; this is sufficient to compile a detection count to be used as an index of local activity. Seismic sensors have achieved ranges of as much as 30 meters for pedestrians and 300 meters for trucks, although susceptible to false alarms from such sources as rain, wind-swayed trees, aircraft, and ordnance detonation.\*

It was apparent from the outset that most of the initial work would deal with assembling a suite of off-the-shelf hardware into a working system (Phase I) using current techniques drawn from the expertise of all three Services; however, it was recognized that more sophisticated, effective versions of the equipment and the system would be possible in later phases.

The DSPG was organized principally as a systems integration group with responsibility for several aspects of R&D management. Specifically, responsibility was apportioned as follows:

<u>Responsibility</u>	<u>Agency</u>
Concept formulation	DSPG
System design & engineering	DSPG
Element design & development	Services
Procurement	Services
Field testing	DSPG & Services
Development	Services
Operation	Theater Commands

So far, DSPG has managed to adhere to this unique charter throughout its life. It is recognized that sooner or later the Services may assume direct responsibility for the development and use of tactical sensor systems. Nevertheless, the speed with which effective field deployment was initially achieved would not have been possible without such a streamlined pan-Service organization.

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\* The range of seismic sensors is highly dependent on local geological conditions, i.e., the harder the ground the longer the range. Under average conditions seismic sensors have shorter detection ranges than acoustic sensors. This has the advantage of enabling emplacement of strings of sensors beside a road or trail which when triggered in sequence indicate trucks or men on the ground as opposed to aircraft or natural phenomena such as storms. The analysts of detections to determine sequential triggering is a manual function aided by X-T plotters and/or chronological logs. The lower ranges greatly decrease the false alarm rate otherwise experienced.

As an adjunct to this responsibility, DSPG maintained top-level working groups composed of military, professional, and academic personnel. The function of such groups was to provide guidance in the continual advancement of the state-of-the-art within their areas of interest and to make resultant information and advances available to the DSPG community. Two groups of particular interest were: (1) AWG\* (Acoustic Working Group) chaired by NADC at DSPG's direction, and (2) SWG (Seismic Working Group) directly under DSPG.

#### NATURE OF THE PROBLEM

As recommended in the 1966 Jason report,\*\* the problem confronting DSPG was to develop a remote, unattended, air-emplaced sensor (and later a family of sensors) suitable for detecting truck and pedestrian infiltration traffic into South Vietnam. There were in 1966 two principal infiltration routes. The main route ran from North Vietnam across the western edge of the Demilitarized Zone (DMZ) into Laos where an organized trucking system existed to carry the flow south and east into South Vietnam.\*\*\* The other less-important route was directly through the DMZ at numerous points including the coastal plain.

The Jason Committee recommended a series of barriers to interdict this infiltration. Near the South China Sea, along the 30-km wide flat coastal plain in the DMZ, a "conventional" ground-emplaced linear barrier of minefields, hard-wired sensors, and barbed wire obstacles were recommended. West of that barrier and covering the rugged hills and mountains near the western edge of the DMZ where ground-emplacement was extremely difficult, a new concept of an air-emplaced and air-supported barrier comprising unattended sensors and minefields was postulated. A similar barrier, or interdiction zone, was suggested for the truck routes in Laos, where political and military considerations precluded a more conventional approach. These three sub-systems or barriers were collectively referred to as the "infiltration interdiction system."

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\* Later known as SSG (Special Studies Group).

\*\* IDA Study S-255, 15 August.

\*\*\* Best estimates ranged to 50,000 men manning this logistics system along the Ho Chi Minh Trail, defended by about 35,000 troops and numerous anti-aircraft installations. (Source: Newsweek magazine, March 1971)

For the linear-barrier/strongpoint-obstacle system intended for the DMZ a group of hand-emplaced, hardwired sensors already under development by the Army was selected to augment physical fences and guard towers. That system--sometimes referred to as the "McNamara Wall"--was never implemented as originally envisioned for a variety of reasons. Hard-wired sensors and equipment played only a limited role in operations. Because they are more conventional in nature and have less potential for future applications than the more advanced concepts, they will not be treated here.

For the air-monitored applications, a new family of air and hand delivered, remote, unattended sensors was developed by DSPG from Naval sonobuoy launchers; this family of RF link sensors formed the basis of sensor surveillance along the Ho Chi Minh Trail and in South Vietnam.

The emphasis in this new sensor program had been directed primarily toward detecting trucks and personnel moving in heavily foliated areas, but objectives included detecting swimmers and watercraft--powered, poled, sculled, or paddled--to stop infiltration along canals and rivers as well as to defend bridges and harbors.

#### PHASE I

The overall sensor program has proceeded in five phases. Phase I consisted of the first year's efforts to achieve a workable system in the field with minimum delay. Each succeeding phase--Phase III is current and Phases IV and V are in planning--incorporated lessons learned, requirements recognized and technological achievements realized during those preceding.

Phase I was characterized by a sense of urgency, multiple development options, CONUS (Continental United States) (rather than SEA) generated requirements, and a continual tradeoff of attainable-versus-optimum capabilities. The bare-bones concept containing gross estimates of quantities and technical characteristics had to be refined during the compressed development and procurement period. Though the theater provided major contributions in terms of plans for system implementation, time precluded detailed review of quantity and performance requirements. Of the three indices of system management--time, performance, and cost--time was pre-eminent. The DSPG was confronted with the realization that no off-the-shelf hardware existed that met all requirements; thus, the thrust of the first year was to identify the most promising existing components and expedite their modification for initial deployment.

A third type of Phase I sensor incorporates both acoustic and seismic detectors with inter-connected trigger logic such that either the acoustic or the seismic (logical OR) or the acoustic and the seismic (logic AND) are necessary to trigger the unit. When the dual sensor is triggered, it reacts like an acoustic sensor and transmits audio for 10 seconds. This configuration results in lower false alarms from overflying aircraft when the seismic detection is employed.



Phase I Acoubuoys were later modified for several special purposes including:

- (1) hand emplacement with an add-on seismic detector,
- (2) triggering by receipt of an RF signal from the crushing of a small noiseless RF generating button bomblet,
- (3) detecting automotive ignition.

Under average operating conditions (one percent duty cycle) these buoys have operating lives in excess of 45 days.

A fourth type of sensor, characterized by the MAGID T-3, detects targets magnetically. False alarms decreased (as from distant lightening) by coupling this with other sensors. Ranges of 3-6 meters for a moving man with a rifle and of 15 meters for a 2-1/2 ton truck have been obtained reliably and with minimal false alarms.

To complete the infiltration detection system, sensor data is linked by VHF to a surveillance center. Surveillance centers range from small, company-level units monitoring local fields or strings of sensors with portable readout equipment to the theater-level Infiltration Surveillance Center (ISC) at Nakhon Phanom, Thailand. The ISC receives sensor transmissions from relay aircraft (signal converted to UHF by aircraft) flying over South Vietnam. The ISC reports infiltrations to local commanders for response action and also keeps track of overall infiltration into South Vietnam.

The initial utilization of the air-emplaced remote sensors (Phase I) in Vietnam was auspicious. The first sensors installations were planned for mid-January 1968 along the western edge of the DMZ and in nearby Laos. However, the siege of Khe Sanh had just begun, and General Westmoreland decided to utilize the new sensors there instead. Fortunately, the Marine gunnery officer at Khe Sanh happened to have been one of the principal military advisors assigned to the 1966 Jason summer study. Results were dramatic: artillery fire was vastly more effective since the enemy's positions were known much more accurately even at night. In fact, the sensors are officially credited with saving Khe Sahn.

Based on this experience and a subsequent employment in the A Shau Valley, General Westmoreland decided that the sensors should be introduced to units throughout Vietnam.

## PHASE II

Second generation Acoubuoys incorporate two principal improvements over Phase I: remote command capability for operating mode, and Line Spectrum Detection electronics. The command capability in Phase II sensors enabled the system operator to:

- (1) select a real-time mode (RT) wherein sensor ID is transmitted upon detection.
- (2) select a non-real-time mode (NRT) wherein the sensor itself counts and stores detection events (triggers) for subsequent readout.
- (3) check sensor status.
- (4) readout the current event count.
- (5) Command Audio where on command a preset length of audio (nominally 10 seconds) is transmitted.

Phase II seismic sensors also allowed for items 1 through 5 above plus:

- (1) check sensitivity of the variable gain threshold logic.
- (2) change sensitivity by increasing one in a cyclic seven setting range.

The advantage of this command capability is less crowding of communication channels--there are only 31 in Phases I and II--and a lower duty cycle for longer sensor life. This technique enables mutual interference between sensors on the same channel to be reduced or often eliminated.

Line Spectrum Detection, used in some of the Phase II acoustic sensors, is the first complex in-sensor signal processing. The sensor uses a narrow processing band to lock onto acoustic noise generators in the 62- to 142-Hz frequency range. Having locked onto one spectral line in the spectrum with a strong concentration of energy (such as the principal firing frequency of a truck engine), the sensor tracks this line as it varies with engine speed. The variations (dither) form a recognizable pattern characteristic of trucks, which can be used to classify targets and thus reduce false alarms.

Phase II saw the introduction of other improvements as well, including physical modification to enable air emplacement from a 550-knot F-4 aircraft instead of the much slower P-2.

### PHASE III

Phase III witnessed significant improvements in the communications capabilities of the remote sensor system. The requirement for this capability came about through the great increase in sensor use throughout Vietnam. By the summer of 1969 there were about 1500 sensors in use at any one time, far more than had been anticipated by DSPG in Phase I and II days. In Phase I and II, there were only 31 channels used in the DSPG-assigned 161-174 MHz VHF band, each with 27 identification codes for a total of 837 uniquely identifiable sensors per system. Phase III expands the system to a theoretical limit of 640 channels with 64 codes each for a maximum capability of 40,960 sensors per system. However, in practice there are several constraints that preclude full exploitation of this enormous capability. The inherent frequency instability of the transmitters and the bandwidth instability of receivers preclude use of all channels; as a guard, alternate bands are used to prevent interference. Phase III equipment must operate concurrently with Phase I and II equipment. This, as well as other radio frequency interference (RFI) problems, effectively reduces the available channels further to 116 rather

than 320 for Phase III. Thus, 116 channels with 64 codes gives 7,424 uniquely identifiable sensors possible in one system. Since the deployment plans through mid-1974 call for at most about 3,500 sensors to be emplaced and operating at any one time, the communications bottleneck should be cleared.

Another significant improvement in Phase III is the change from analog to digital data transmission by sensors. Three types of messages are possible:

- (1) Type 1 - 18 bits long that gives sensor ID only
- (2) Type 2 - 24 bits long that gives ID plus either the gain setting of the seismic amplifiers and mode setting or the tally of activations recorded in the non-real-time counter
- (3) Type 3 - 18 bits for the ID plus from 1.5 to 20 seconds (preselected) of acoustic audio (analog).

Power output of the sensors is raised to 3 watts in Phase III from the 1 watt in Phases I and II.

The net effect of the increase in channels, digitization and power is a considerably heightened protection against interference and jamming.

Additional improvements introduced in Phase III include modular sensor construction, five Common Modules usable by all types of sensors, improved quality control, and standardization of controls on hand-emplaced sensors. Modularity allows easier in-theater repair and parameter selection (ID's, frequencies, etc.) and simplified logistics. Improved reliability decreases system costs and decreases problems in the field. Standardized controls greatly ease personnel training and simplify field use.

#### PHASE IV/V

##### Background

In August of 1968, at the direction of the Director of Defense Research and Engineering (DDR&E), a committee of senior scientists and military personnel was tasked with review of the whole DSPG sensor program for Southeast Asia. Topics reviewed concerned not only the technical and operational aspects but also the managerial and financial aspects of the program. This group (designated the IGLOO WHITE/DUEL BLADE/DUCK BLIND Evaluation Committee) was primarily concerned with improving our posture in Southeast Asia in the following two years; nonetheless, the committee quickly recognized the inherent merit of remote sensor systems applied in other areas of the world to a wide range of battlefield situations. Consequently, the committee entered the recommendation that DSPG should lay longer-range plans beyond Phase III.

The Joint Chiefs of Staff (JCS) accepted the committee's recommendations but indicated that development plans beyond Phase III should be jointly undertaken by DSPG and the Military Services. It was felt that this would assure optimum system alignment with realistic future Service needs in support of traditional roles and missions.

In accordance with the Committee's recommendations and the requirements set by the JCS, DSPG announced that it would begin working with the Services to develop plans for Phases IV and V. Further, the time-frames for each were established as mid-1972 and mid-1975, respectively.

Each Service formed a study panel to consider applications of sensor and sensor-related technology in the time frames of reference. Their thoughts were collected by DSPG and they formed the basis for the document entitled "Phase IV/V Development Planning Study" dated 18 April 1969. This document provided a basis for further refining Phase IV/V plans which ultimately lead to specific operational requirements.

### System Concept

Phase IV may be considered an improvement of components and functions generally within the framework and organization of the Phase III system. Insofar as possible, Phases III and IV will be compatible. Phase V is primarily concerned with advanced developments and major reorganization of the concepts and modes of operation.

The Phase IV/V concept calls for worldwide operational employment. Because of this, the system concept calls for a high degree of mobility, flexibility, and improved modularity with individual applications satisfied through careful tailoring. The overall goal of the system, in any locality or battle environment, is to provide data for intelligence analysis and planning and rapid tactical reactions.

All Phase IV equipment including readout, relay, and data processing devices will be mobile or transportable to insure quick deployment capability. Equipment used by the various Services will be compatible and interchangeable as much as possible. The system will be modular to enhance flexibility, reduce R&D costs, decrease logistics problems, and permit a variety of units to be preassembled on a contingency basis.

### Areas To Be Improved

The joint DSPG-Services study pointed out several areas where improvement is needed. Included are:

(1) Radio Frequency Interference (RFI) and Electronic Counter Measures (ECM) Vulnerability. Though not a particular problem in SEA, against more sophisticated enemies the sensor or communications may well be vulnerable to ECM. In more saturated electromagnetic environments, RFI becomes a problem. Possible solutions include:

- New modulation techniques (e.g., burst)
- Narrower bandwidth
- Cipher devices
- Directional antennas

- More appropriate choice of frequency bands
- Spread Spectrum Techniques

(2) Navigation and Position Finding. Even in Phase III, knowing the position of sensors to within tolerable limits, particularly if air-dropped or artillery-emplaced, poses something of a problem. It appears that an integrated system using LORAN C (or perhaps D) and an inertial platform on the delivery aircraft may be one of the better for air-dropped sensors. Methods for accurately determining locations of artillery-emplaced sensors must still be found.

(3) False Alarms. Aircraft, artillery, and natural phenomenon (e.g., storms, animals, and other such sources) have caused high false alarm rates. Although progress in this area has been made, further attempts will be made to reduce these rates during Phase IV and beyond.

(4) Size, Weight, and Power Consumption. Size and weight are critically important for most sensors, particularly those to be hand emplaced after being carried over long distances. The importance of this tradeoff--soldier vs. buoy weight--cannot be overstated; as weight increases, the number of soldiers required to emplace a given field increases, and the ease with which they accomplish the emplacement decreases. Size also directly affects the ease with which the sensor can be camouflaged. For a given battery, as power consumption decreases, sensor life increases. Reducing false alarms decrease duty cycle and thus increases sensor life. Plans call for better use of micro-miniaturization techniques; integrated circuits are generally not used. In addition, work has begun on developing improved batteries; lighter, more powerful, smaller, and operable over virtually all temperatures which might reasonably be encountered worldwide.

(5) Deployment Techniques. New techniques for more effectively using sensors will be developed. Variables include choice of targets, deployment strategy (including sensor mix), localization algorithms, etc.

(6) Detection Methods. Several new remote sensing techniques and new application of existing techniques are technologically feasible at this time. These include, but are not limited to:

- PECM (passive ECM) - to determine periods of activity, testing, and operation of electromagnetic emitters.
- MTI (moving target indication) - pulsed or continuous wave (CW) electromagnetic signals provide information on moving targets.
- CBR (chemical, biological, and radiological) detectors - to detect the presence of harmful chemical, biological or radiological elements.
- Video - techniques such as slow scan TV or low-light level TV provide remote visual monitoring capability.

- Olfactory detectors - may be used to detect human effluents of enemy personnel, including both land troops and (possibly) swimmers. They also may be used to detect such odors as engine exhaust.
- Methods more effective against underwater swimmers - perhaps active sonar.
- Directional sensors - coupling a directional capability with existing sensors to provide better localization data.
- Direction Finding - by using arrival time, frequency shift (Doppler), and phase shift difference techniques, sensors can be used to localize the target.

Work has already begun in developing these sensors and exploring their applicability. Present day sensors also must be improved.

(7) Delivery Techniques. Current delivery techniques include delivery by hand, slow and fast aircraft (including helicopter), rockets, and mortars. Further improving artillery and rocket delivery capability to employ large-caliber naval guns, larger artillery (e.g., 5-in. guns), and rockets is a Phase IV/V goal.

(8) Satellite Relay. At the present time sensor transmissions are limited to line-of-sight, necessitating mountaintop relays or circling aircraft for monitoring large areas. Both methods are expensive and vulnerable. Satellites will solve the problem if the sensors can communicate directly with them. Other advantages include probable decrease in ECM (and perhaps RF) interference. Investigation of the use of satellites in Phase IV/V has begun. Questions being addressed include:

- Optimal frequencies - sensor-to-satellite, satellite-to-readout station
- Synchronous versus asynchronous orbits
- Capacities, number of channels, etc.
- ECM and RFI vulnerability

(9) Integration with Automatic Data Processing (ADP) Systems. A commander has information available from multiple sources (radar, patrols, reconnaissance missions, etc.) of which the sensor system is only one. All this data must be integrated in some appropriate manner; this suggests the use of ADP systems to process the data. Consideration must be given to the best level at which to introduce ADP. Should the system be fed raw data or preprocessed data? To what extent should data be preprocessed?

(10) Display Capability. Data must be displayed in an easily used manner. This is true at every level of command from the field operator to sector commander. Human factors analyses must be conducted to ascertain the best methods and formats for data display as a function of command level.

(11) Spectrum Analysis. As the ability to discriminate between false and true targets increases, analog information will be used less and less. When analog information is used, a spectrum analyzer would be useful. Such an analyzer could help detect characteristic target lines and possibly characteristic line instabilities and thus help to eliminate false alarms. This analyzer could be either in-buoy or remote (i.e., centralized and used for several sensors).

(12) Friendly Unit Identification. There is a formidable problem, especially in areas of relatively high population density, in classifying targets as to friend, foe, or neutral. Methods must be developed to enhance discrimination capability. For example, recent work indicates that a LORAN transponder carried by friendly patrols can be used for IFF (Identification Friend or Foe) purposes.

(13) Relay Techniques. Even if satellites are used, a need still exists for improved conventional relays. Relays may be ground-based, drone-carried, carried aboard tethered balloons, or reconnaissance aircraft, etc.

## INBUOY PROCESSING ENHANCED DETECTION DESIGNS

### GENERAL

During the beginning of the Southeast Asia conflict, the desire was to develop an air acoustic sensor which would only transmit an RF signal when the acoustic level exceeded a threshold. The purpose of this device, called an acoubuoy, was to allow a field of them to be spread over an area of interest; transmitting only when a target was nearby. The transmissions gave a unique sensor identification allowing the location of the targets to be known. Since the sensors were originally airdropped and parachuted into the jungle at some risk to the deploying aircraft, it was desirable to have the long life sensors; in excess of a month. This was also accomplished by only having RF transmissions when the target(s) were close by. In addition raw audio information was also transmitted, this allowing the receiving site to assist in the classification of the source which caused the threshold to be exceeded. From the very beginning of the conflict to its end the sensor went through many alterations and improvements, including using other influencing elements conjunctively, such as seismic data, but always with the idea of an RF transmission occurring only when a threshold was exceeded. Two types of target sounds were considered in the design of the original acoubuoys for optimized signal-to-noise (S/N) considerations; the first an impulse (explosive) sound and the second vehicle sounds. Early in the conflict, the first requirement disappeared and the second was emphasized by more mature sensor design. Later on, classification was augmented by analysis external to the sensor; these efforts are reported in the next section. In approximate chronological order a summary of the enhanced detection investigations follows.

### Optimization for the Phase I Sensor

Early in 1967, a series of experimental studies were conducted and reported by references 3 through 6 in an attempt to determine the nature of propagation transmission characteristics in various medias; these efforts later summarized in reference 1. Reference 7, an unpublished working document, summarized the filter parameters of the Phase I sensor for both impulsive and vehicle sound for a typical jungle environment with the source located at 200 meters. Figure 1 is the block diagram of the Phase I sensor with the transmitter staying on approximately 30 seconds after the threshold is exceeded in order to allow sufficient time for aural target verification.



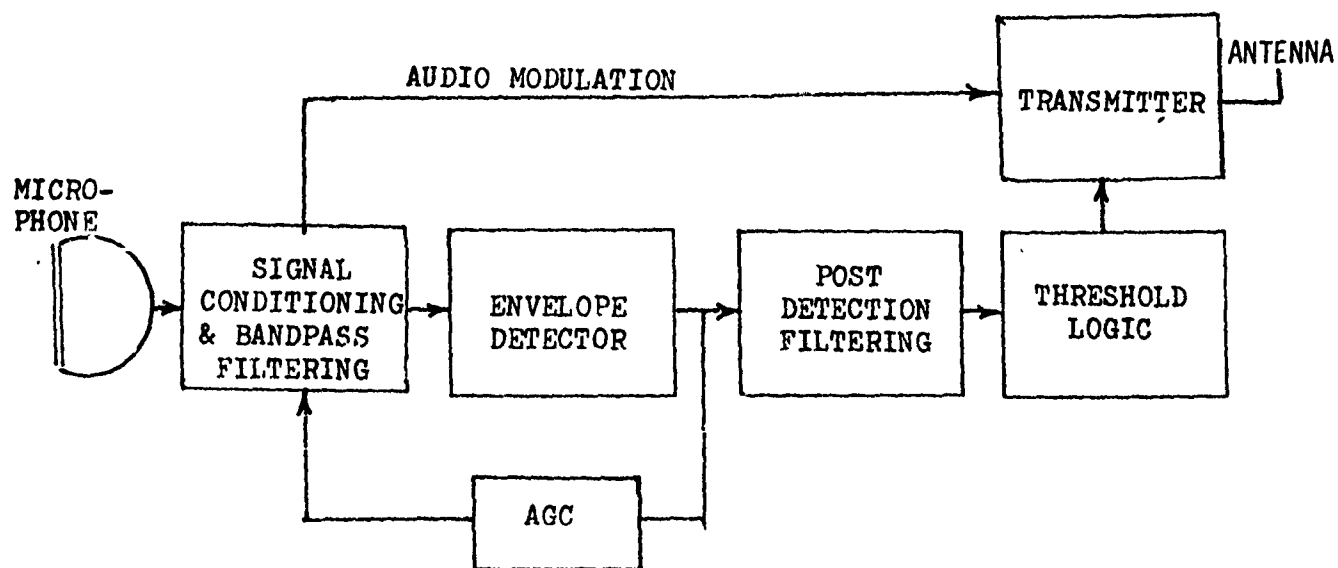


FIGURE 1

Parameters optimized were the predetection filtering, AGC time constants and post detection filtering.

Impulsive Noise Source - For normal jungle ambient noise background of wind, rain, and some aircraft traffic revealed that a predetection band pass between 300 to 500 hz. was a good compromise for optimizing the signal-to-noise ratio. Considered in this compromise was the adverse absorption of high frequency sounds and the presence of fauna noises above 500 hz. Likewise, the lower limit was influenced by the presence of wind gusts and thunderstorms causing excessive false alarms. In addition the post detection time constant and the AGC attack time constant also were equally important. In particular, the nature of the impulses of the explosive sound, even at a range of 200 meters, allowed in excess of 200 per second AGC rates and a post detection time constant of around 10 milliseconds. These values essentially suboptimize the rise and fall time of impulsive sounds against the environment which caused false alarms. This combination of prefiltering, post detection time constants coupled with a fast AGC system proved very satisfactory results, and as a total system gave a high degree of performance against a variety of impulsive sounds with simple circuitry.

Vehicle Noise Source - For the same Phase I logic, i.e., simple input bandpass filtering, amplification, envelope detection, with AGC and post detection time constants, vehicle sources were also being considered for circuit optimization. Because of the similarity of aircraft to truck noises, the problem became more difficult by an additional problem caused with desensitization by wind noise. A compromise recommended for operational use was a predetection band of 90 to 200 hz.; the upper limit tending to minimize aircraft and transient noises while the lower limit attempted to give some assurance of at least one octave of data being covered so that at least one discrete component from an engine source would be present. An additional problem incurred with the presence of wind on the one hand desensitizing the system in a steady state condition by raising the noise threshold, while on the other hand causing false alarms when it was gusting. These problems were minimized by the use of wind screens around the microphone which tended to break down the turbulence generated noises around the microphone housing of the sensor, though it did not reduce the overall ambient noise due to the wind rustling of the leaves, etc. The automatic gain control (AGC) attack time was found to be optimal around 0.1 d per second with a post detection time constant of around 300 seconds. This time constant allowed very slow changing noise environments overall noise levels, but still allowed a normal transmitting of targets to increase the noise level above the threshold level without being completely compensated by the AGC of the system. By the same token, the post detection high time constant was found appropriate in reducing false alarms due to impulsive type sounds.

Tests for both sensor designs were done to demonstrate the effectiveness of these conclusions. They were performed in very heavily foliated sites in Panama, in the pine tree sandy environment of Eglin Airforce Base in Florida, and in the wooded environment of eastern Pennsylvania. The results of these tests showed that the sensors performance were in agreement with the analytical interpretations from the laboratory studies. These two operating parameters were eventually compromised for tactical use with average parameters used giving some performance for both impulsive and vehicle noise sources.

### Two Band Comparative Concept

During this same period of time, more complex techniques were investigated in order to increase the effectiveness of the vehicle detection logic. One of these techniques was called the "two band" concept. In this concept, information was processed separately in two different frequency bands then compared to determine if a threshold was exceeded. Figure 2 represents a block diagram of this approach.

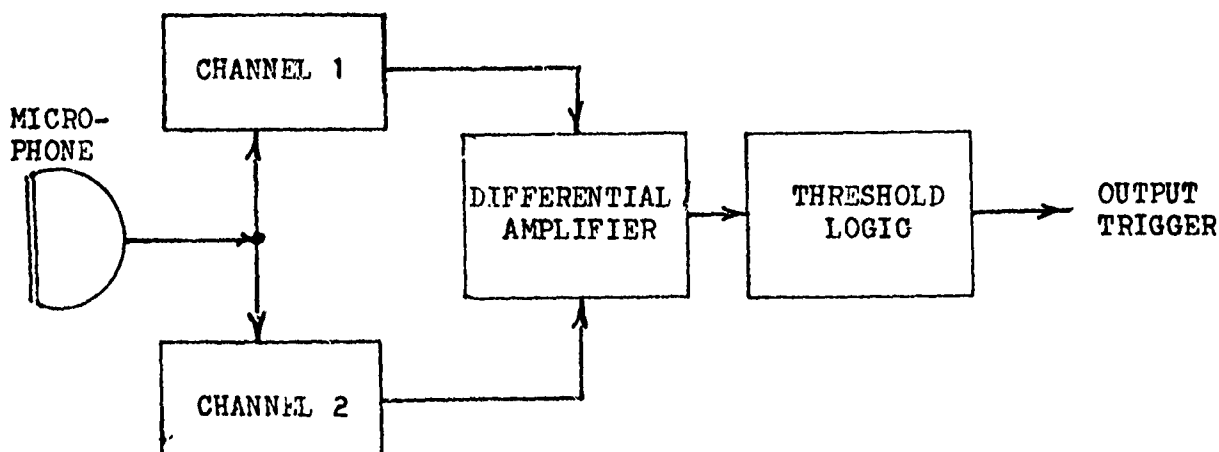


FIGURE 2

One particular effort studied had the two filtered channels being 100 to 200 hz. and 300 to 500 hz., with the DC output of the envelope detectors amplified logarithmically then used to drive a difference amplifier, when the output of the lower spectrum exceeded the upper frequency band a detection would be called. The philosophy behind this approach was that many of the sounds causing false alarms, including wind gusts, aircraft, jets and animal noises, had a rather broad band spectrum and would tend to raise both levels at the same time while vehicle traffic had the majority of its information in the lower spectrum. This technique proved to be quite successful and adaptive for a variety of noise conditions and did give performance superior to the single band envelope detection previously mentioned. Though the success had it considered a viable candidate for the next phase of sensor development, it was never implemented when it became more desirable to take advantage of phase lock loop line tracking and the appropriate line stability measuring logic.

### Line Tracking Logic

During early studies it was found that with a high degree of assurance a major discrete spectral component from a reciprocating engine from trucks would occur in the range of 60 to 140 hz., while reciprocating engine aircraft gave outputs emphasizing higher frequencies. Advantage of this was used in the Phase II acoustuoy design, where a swept phase lock loop detector of approximately 2 hz. analysis resolution would locate a discrete component in

the 60 to 140 hz. band and lock in on the line and continue to track that component through doppler changes and short term instabilities, caused by engine RPM changes due to rough roads, driving conditions, etc. The immediate advantage of this approach was the increased detection range and reduced false alarms against normal background jungle noises, which being of a non-discrete nature did not allow line tracking. Detection ranges using this line tracking approach tripled that of the envelope detection approach, with one new problem being too great of a performance with cases of trucks being detected many miles away. Even with the frequency spectrum upper limit of 140 hz. there was still an aircraft false alarm problem due to reciprocating engines. One particular technique that was found to be quite successful in minimizing this problem was a so called dither logic where the nature of the instability of the discrete frequency components being tracked was noted and the degree of instability of the line tracking used to cause a target alarm. The philosophy was that aircraft engines do not have the short term instability of trucks due to the use of constant speed drive propeller driven systems. This proved to be an extremely effective technique and the Phase II G sensor used this spectrum analysis/phase lock loop and dither logic very successfully. Figure 3 is a block diagram of a typical Phase Lock Loop System. At this particular time a greater emphasis was placed on coupling acoustic information with seismic data in order to completely overcome false alarms by aircraft. In particular when both seismic and acoustic data occurred together, a high degree of assurance of a valid close by truck or convoy could be determined. This was because the false alarm mechanisms of acoustics and seismic were different, i.e., the seismic false alarm was caused by guns and shell impact, while the acoustic false alarms were mainly due to reciprocating aircraft.

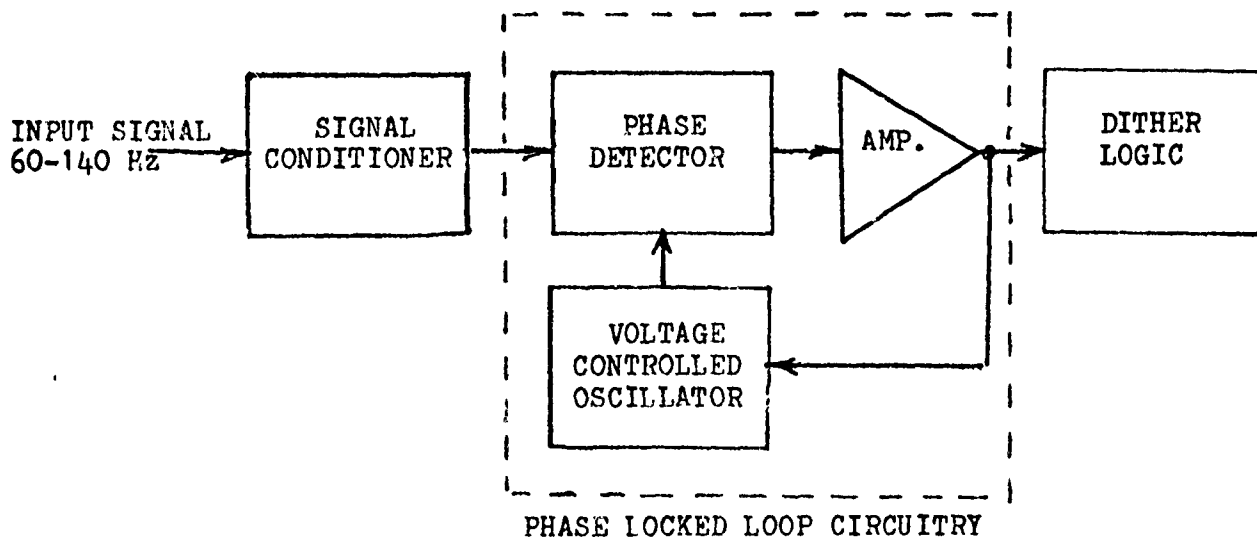


FIGURE 3

### Vertical Directivity

In addition to the pre and post detection processing oriented approaches mentioned above to enhance detection, there existed another approach which is particularly advantageous to minimize the false alarm and desentization aspects from aircraft. This approach, known as vertical directivity, took into account that the targets of interest, whether personnel or the vehicle, were in a horizontal plane from a free swinging parachuted acoubuoy, or its counterpart the vertical implanted spikebuoy, while the aircraft were above the horizon and approaching 30 degrees when they were close inbound where their noise level would be the most detriment. As such, it was recognized that either a horizontal major lobe or vertical null would tend to enhance overall system performance with or without other circuit logic. In actuality this approach was found to be advantageous, with many different technical avenues available for consideration. The first of these was the use of microphones which by themselves had directivity and in particular a null in the vertical direction. One of the more classic forms of this was the cardioid microphone, well known in the entertainment world, with the null placed away from the performer to prevent feedback and extraneous noises from reaching the microphone. In this case the null of the cardioid would be vertically mounted. In many applications this was quite satisfactory except for the recognition that in much of the environment in which sensors were used there was a considerable amount of ground reflection and therefore the aircraft noise could still be seen via the front part of the cardioid. The second approach was the use of microphone elements connected by phase shifting networks. This approach can give a near omnidirectional pattern in the horizontal dimension while still maintaining a null in the vertical direction. This approach overcame much of the deficiencies of the ground reflection. The "Donut" pattern and "Cardioid" were particular versions of this approach where combinations of the above were used to give other patterns of a more desirable nature and were investigated throughout the Southeast Asia conflict. Appendix A, reference 8 was a summary of some of these more mature microphone directivity efforts.

## CLASSIFICATION TECHNIQUES

## GENERAL

From the very beginning of the sensor development it was recognized that classification was one of the primary areas of technical concern in the Southeast Asia conflict's sensor development program. Originally, classification was addressed by the process of optimized detection for a particular class of targets. This was of primary interest for both the Phase I and Phase II sensors which would only transmit when its internal circuitry had a processed signal exceeding a certain threshold. It became apparent that the similarity of aircraft noises and vehicle traffic did not allow for a high level of probability of detection with low false alarms. Although more mature in-buoy processing techniques were devised for the Phase II sensors using phase lock loop detectors, the need for lower false alarms and more intelligence required additional classification maturity. This concern justified the use of human operators, aided by additional equipment, who would pass final decisions as to the classification of a target(s). The sensors at this time had the ability to transmit raw acoustical data via RF link to a receiving site, either automatically or under command from the receiving site. Taking advantage of techniques used in ASW, and recognizing the similarity of the classification problem for the submarines, aircraft, and trucks relative to the engine driven acoustical sources, Navy ASW spectrum analyzing equipment was adapted and operators trained to assist in the final classification. Operationally, an operator attempted either aurally to determine the source identity or by the use of spectrum analysis techniques which allowed a time versus frequency versus amplitude information to be visually displayed. This latter effort started in 1967 and reached a rather high degree of maturity in both the availability of training and classification manuals by 1972, and it proved to be quite successful in assisting in the final target(s) classification. During the end of the conflict, investigation had been started into automating the classification process by use of matrix and/or decision tree logic. These efforts were in the laboratory investigation stage by the end of the conflict with the technology continued as part of the Army's Remotely Monitored Battlefield Surveillance System (REMBASS) Program.

Although not a part of this report it is appropriate from a conceptual standpoint to comment on the use of multisensors input for the purpose of classifying. This takes on several different forms where the use of direction and/or localization techniques also becomes a classification aid. In some of the concepts that were investigated, the real time localization, either by directional or time of arrival information, allowed for the tracking of a suspected target(s) where the rate of change of the bearing information or the movement of the target location alone would differentiate between aircraft and much slower moving truck traffic. Although at this time an apparently obvious concept, it was of significant importance in the total system concept and was used for classification purposes. Another form of multisensor input took advantage of seismic data which coupled simultaneously with acoustic devices would take advantage of this and would assist in the classification.

Seismic sensors by themselves took advantage of earth conduction and was relatively insensitive to aircraft noise, by itself marginal in effectiveness. It was appreciated that by cross-coupling the logic of two systems, the lack of the presence of some seismic activity and acoustic information could minimize the false alarm rate in total. To follow is a description in more detail of the classification aid for both spectrum analysis and machine aided techniques.

### Spectrum Analysis

The use of spectrum analysis to assist in classification was first operationally used in the SEA conflict in late 1967 where U.S. Navy equipment, the AN/AQA-3/4 indicator group, was placed in operational use at the receiving sites. These were later replaced by specifically designed equipment developed by the Naval Air Development Center, Warminster, PA. References 9 through 14 are training/classification aided documents produced and used during the late 1960's and through the early 1970's. Appendix B, excerpted from reference 10, describes the academics with examples of this classification process.

### Machine Aided

In order to assist the operator in classification, it became apparent that much of the "memory" and arithmetic operations of the classification process could be automated - requiring only the inputs of the characteristics of the discrete components as displayed by an analyzer. Two major efforts reported in this effort are contained in reference 14 for general discussions, and reference 13 for a very detailed discussion including considerations for seismic data. Extracts from reference 13 are appendix C of this report. Also included is a computer program which demonstrates this concept.

Although not done during the conflict itself, it is appropriate to comment on the machine aided techniques used for classification which adapts itself for in-sensor processing. Although the techniques can be implemented for a general purpose computer, an extensive analysis was done for various seismic and acoustic target classifications, reference 15. Extracted from this report are the following comments which relate to the classifier approach presently used for in-buoy classification.

## GENERAL PROPERTIES OF CLASSIFIERS

The conventional approach to classifier design has been guided by the techniques of pattern recognition. As described previously, a large number of samples consisting of signatures representing each class of targets of interest are selected as a design data base. Selected measurements (features) are taken from each of the signatures in the design data base. For instance, one such measurement may be the number of zero crossings in a 1-sec record of a signature. The series of measurements taken from each signature constitutes a feature set  $(X_1, X_2, \dots, X_j, \dots, X_m)$  where  $X_j$  is the  $j^{\text{th}}$  feature.

A function of the feature values is devised to reduce the feature set to a single real number. The decision process is implemented by defining this function in such a manner that, hopefully, a unique set of values of the function will exist for signals from each class of targets, independent of operational and environmental conditions. In this event, the target class can be assigned strictly from the value of the function.

Although more complex functional forms (such as quadratic functions) could be used, the classifiers investigated in this study use a linear discriminant function as a basis for classification and are therefore known as linear classifiers. The form of the linear discriminant function is given by

$$s_k = W_{ok} + \sum_{j=1}^m X_j W_{jk}$$

where

$s_k$  = linear discriminant function

$k = 1, 2, \dots, n$

$n$  = number of classes

$W_{ok}$  = initial value of linear discriminant function dependent on the prior probability of occurrence of class  $k$  (also referred to as a weight)

$m$  = number of features

$X_j$  = value of feature  $j$

$W_{jk}$  = weights associated with class  $k$  and feature  $j$



The class is chosen for which  $s_k$  ( $k = 1, \dots, n$ ) is a maximum (i.e., relative to the other values of  $s_k$ ). The  $W_{jk}$  and  $W_{ok}$  are selected in a manner that minimizes some function of the errors between the desired and measured values of  $s_k - W_{ok}$  for the particular class. There are several approaches for minimizing the error; therefore, different investigators may obtain different weights from the same design data base.

Typical features used are:

- Time between events (time between threshold excessives)
- Time between time domain signatures, axis crossing (relates to frequency)
- Consistency of b. above (stability)
- Smoothness (stability of levels)
- Energy rates. (similar to "two band" concept of the section titled "Inbuoy Processing Enhanced Detection Designs")

Efforts are still continuing throughout 1978 to find a more meaningful parameter and better models in an effort to improve performance of these techniques.

## T A R G E T   L O C A T I O N   T E C H N I Q U E S

## GENERAL

During the Southeast Asia conflict there was a continuing requirement for obtaining the location of acoustical sources. This need occurred at the very beginning of the DSPG program where it was desired to note the position of personnel as they went through foliage and activated small explosive charges. The need was re-emphasized when the location of motorized vehicles became a very important factor at the end of the conflict. A variety of techniques were used or considered in meeting this localization requirement including simple sensor activation to indicate presence, directional microphones, forms of phased arrays, and use of time of arrival information. The following sections address as appropriate each of these concepts.

Proximity Determination

This concept represented the simplest and in many cases the most effective of all the location concepts where sensors would be placed in an area, their location known, and the pattern of activations allowed for not only the approximation of a target(s) position but also its apparent movement. On the Ho Chi Min Trail, this concept got its greatest emphasis where a series of acoustically sensitive acoustic and/or seismic sensors were placed at strategic points by the trail. Normally four or more were placed parallel to the trail, spaced hundreds of meters apart and hopefully with the assurance that one of the sensors was close enough to the trail to ensure detection by vehicle traffic. At control sites where the reception of the activated sensors and their identification code were noted, the initial presence of a target transversing down the trail was noted by a sensor activation and then timed at succeeding sensor groupings spaced 4 kilometers away to allow the rate of advance of the vehicles to be determined. Historical information was used to determine the approximate range of initial "turn on" to a sensor in order to operationally determine on an extrapolated basis where the vehicles would be located for strike operations. Greater sophistication for this analytical process was used later during the conflict; such as using rather mature computer installations for data keeping (location and time of sensor activation) and statistical techniques to extrapolate target positions. This technique was augmented by the use of raw audio information to determine the time of the closest point of approach of the target(s), using techniques such as loudness information or doppler shift on discrete data processed by the spectrum analysis techniques discussed in the previous section. This proximity determination by either activation pattern and/or augmented by the use of the closest point of approach by doppler shift information or loudness information gave location errors between 20 to 30 percent of the average spacing between the sensors. This was done so that with a 4 kilometer sensor spacing on a trail it gave some sort of assurance of target knowledge within 1 kilometer, normally sufficient for alerting strike aircraft. These accuracies were complicated whenever ducting took place, i.e., long range propagation of acoustical sounds due to temperature inversion. In this case it was not inconceivable that a close-by target would not be detected due to a hill shading the sound coming via direct path propagation, but that sound

from another direction would be seen at a far greater distance. It was these anomalies that caused considerable concern at the very beginning of the conflict. Instances were even noted where sounds from fixed sources, such as power plants, would activate these sensors from a distance miles away. It was the use of the doppler shift, the loudness of the transmitted audio information that overcame some of these deficiencies with the lack of presence of a doppler shift that would indicate that the target had not had a closest point of approach or that the aural nature of the sound from a far away source has a different quality due to the selective filtering action of the environment. Both of these factors became manual inputs to the final target location determination.

### Direction Determination

One of the more meaningful ways in assisting in localization and classification is to note the direction of a target from a sensor and to determine its bearing rate of change. These two pieces of information along with some idea as to the sensitivity, i.e., maximum range capability of the device, aided in localization and classification. Although never operationally used to any degree in the Southeast Asia conflict, the usefulness of directional information was recognized. A variety of concepts were evaluated and generically fell into three categories:

1. Inbuoy Bearing Determination - In this case the use of two gradient sensors and one omnidirectional sensor allowed the unique determination of bearing information sent by RF in a coded fashion. This system is described in appendix D and reference 16.

2. DIFAR Processing - In this concept the word DIFAR is used to show its similarity to the underwater concept, where unlike the inbuoy processor above, the three sensor channels, two directional and one omni, are multiplexed together and via the RF link transmitted back to a demultiplexer and spectrum analyzer for bearing information. The existence of these in the Navy made this concept from a risk standpoint very low, but the modifications to the existing sensor and RF relay link device made it unattractive during the conflict itself. The results of an experiment using this concept is described in appendix E extracted from reference 17.

3. Arrays - In this concept more than one sensor would be activated at the same time and phase information used for bearing determination. This concept was used under more than one circumstance satisfactorily in the conflict; its use became more feasible with the presence of more mature acoubuoys which allowed for a command feature where the sensors could be commanded from a remote site to transmit raw audio information when desired. A discussion of the academic aspects for a linear array are presented in appendix F, extracted from reference 18. Appendix G, reference 19, is a survey of all of these techniques. In summary, it can be said that the concepts had meaningful qualifications and could be implemented with low risk if required.

### Comparative Signal Strength Techniques

With the advent of the ability to command on a field of sensors, the location of an acoustical emission by comparative signal strengths was considered. In this approach, which relates back to World War II in the anti-Submarine Warfare forces, one would listen to sensors in a field, and by noting the signal strength determine the approximate location of a target, this being replaced by automated computer techniques as time went on. Although intuitively assumptions are made such that the propagation behavior was well behaved, i.e., ducting per se is not a major factor or if known can be eliminated, then the process is well founded. Appendix H, extracted from reference 20, is a report done at the end of the conflict, which although it emphasizes the results for underwater behavior shows the academics involved in the factors which influence the answers. Tests were run on actual data in the ocean and comparatively accurate results were obtained, especially when it was assured that direct path propagation was present.

### Location by Doppler Information

In addition to the determination of a time of closest point of approach by doppler shift, a location can also be determined giving both range from the sensor to the target and its speed and requires only one sensor. Although this was not used extensively during the conflict, the concept has had extensive use within the United States Navy for location of submarines. Other related concepts were devised where multisensor/doppler information was used for location, course, and speed determination. In general, this concept was not feasible during the conflict due to the requirement for many sensors to simultaneously detect the same target. Appendix I, extracted from reference 21 is the first concept using a single sensor, while appendix J, reference 22 is an academic discussion of the second concept.

### Hyperbolic Fixing

An early academic discussion and derivation of this concept is contained in appendix K, reference 23. Of all the location systems that were devised in response to the Southeast Asia conflict, the one that had the most visibility was in response to the location of guns or impulsive sounds by hyperbolic fixing. During May of 1972, emergency funds were released for the purpose of expediting the development of an experimental acoustical artillery location system for possible use in SEA. The particular proposed acoustical artillery location under investigation, called "ANNIE OAKLEY", was closely related to existing acoustical gun location systems, such as the Army's GR-8, but this proposal had several features designed to improve operational usefulness. Nonreliance on hardwired sensors, computer software techniques which tend to reduce the CEP (circular error or probability) of gun location while simultaneously reducing the false alarms, and a design philosophy which wholly automates the gun location process were specific improvements over existing systems. Figure 4 is a block diagram of the envisioned system operating through an RF link.\*

\* Appendix L, reference 24 are excerpts of the final report of the tests performed on this experimental system.

The concept had been under investigation since late 1967 with original support coming from DDR&E (Director of Defense Research and Engineering) and ARPA (Advanced Research Projects Agency). The original effort was not operationally useful - mainly due to the lack of development effort on the concept - but follow-on analytical efforts by the Navy revealed sufficient promise to permit continued support from the Army. Subsequent testing revealed an accuracy better than 100 meters CEP for sensor spacing averaging 3 kilometers surrounding the target; the geometry of the sensor field to the targets affecting accuracy.

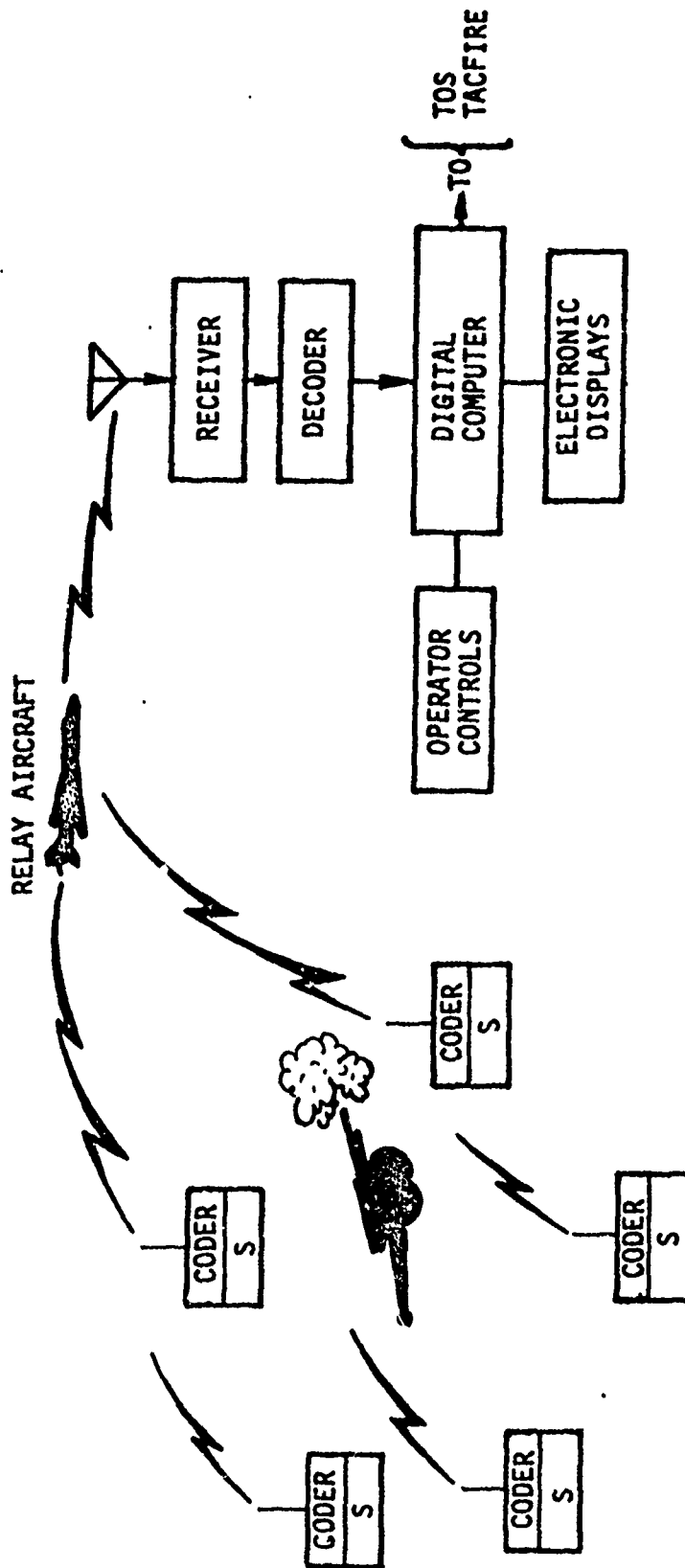


FIGURE 4 - Block Diagram of ANNIE OAKLEY System

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APPENDIX A

Excerpts from Microphone Arrays Cardonut vs. Line Microphones,

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Unclassified

For all acouhuoy systems it would be very desirable to attenuate incident energy which has an angle of arrival greater than  $10^\circ$  above the horizontal. This energy almost always would be that radiated by aircraft. The most effective technique to perform this attenuation would be through the utilization of vertically directional microphones.

Two general implementation techniques have been investigated:

- a. line microphone arrays
- b. arrays derived from the LIMACON family

The polar equation of the LIMACON family is given by:

$$f(\theta) = m + (1 - m) \cos \theta$$

Especially interesting in this family of microphone responses is the first order "DONUT" pattern and a downwardly oriented "CARDIOD" pattern whose responses are given by:

$$f(\theta) = \cos \theta$$

$$f(\theta) = \frac{1}{2} - \frac{1}{2} \cos \theta$$

Still another pattern is the "CARDONUT" whose polar response is given by,

$$f(\theta) = \sin \theta \left( \frac{1}{2} - \frac{1}{2} \cos \theta \right)$$

Each of these configurations is omni-directional in the horizontal plane. The polar response pattern of these microphones is shown in Figure 1.

In the absence of ground reflections, the CARDIOD microphone would offer the simplest, if not the most effective solution. The reflection coefficient is not known with certainty. If it were more than 50% it would have no more advantage than an omnidirectional microphone. The first order DONUT microphone can also be made very simply, however, it does not offer sufficient reduction of overhead noises. At  $45^\circ$  it promises only 3 db reduction of overhead noises. Assuming that a CARDONUT array could be fabricated, it offers the greatest reduction of overhead sounds. Even at  $50^\circ$  the level is reduced by more than 10 db.

Better directivity indexes are achievably with long line microphone arrays. To obtain an acceptable directional pattern ( $25^\circ$  beam width at the 10 db down points and maximum side lobe level of -15 db) requires at least six elements in the line. At a geometric mean frequency of 89 Hz (band of 50 to 150 Hz) and even spacing of  $\lambda/2$  between elements, the length of the line would be 37 feet. The polar

pattern of this line array is shown in Figure 2A. Figures 2B and 2C show the deterioration in pattern at the extreme frequencies of 50 and 150 Hz. The -10 db beam widths are seen to be changed to  $48^\circ$  and  $15^\circ$ , respectively, and the max level lobes to  $-12\frac{1}{2}$  db and -10 db, respectively. For comparison, the CARDONUT polar pattern is shown in Figure 2D. For arrival angles of less than  $50^\circ$  (re horizontal), all parts of the directivity pattern fall inside the CARDONUT envelope. From  $50^\circ$  to the vertical ( $90^\circ$ ) the CARDONUT is far more effective. Because the beam pattern is symmetric about the horizontal, ground reflections, as seen by downward oriented lobes, could very possibly further degrade a line in its ability in reducing the SPL radiated by an A/C.

A rule of thumb used when measuring polar responses of transducers is to place the complete array at least 100 times the array dimension away from any reflecting surfaces. That spacing insures that no more than 1 db of pattern degradation is suffered. For a 37 ft. array, such as is required for the subject problem, a spacing between the last element and the ground should be 3700 ft. A CARDONUT array would require about 10 times 10 inches or about 8 ft. spacing from reflecting surfaces.

Experience in Panama jungle areas indicate typical tree heights of about 150 ft. One third of successfully hung acoubuoys are less than 50 ft. above the ground and about  $2/3$  hang between 50 and 75 ft. high.

Mechanical problems, as opposed to electronic, are usually more severe as regards reliability. However, even assuming that a suitable deployment technique for erecting the microphone array could be developed, the array will always be in a near field environment causing response pattern degradation. In addition, of the  $1/3$  hung below 50 ft. height, half will probably have the end microphone(s) lying on the ground.

# MICROPHONE PATTERNS

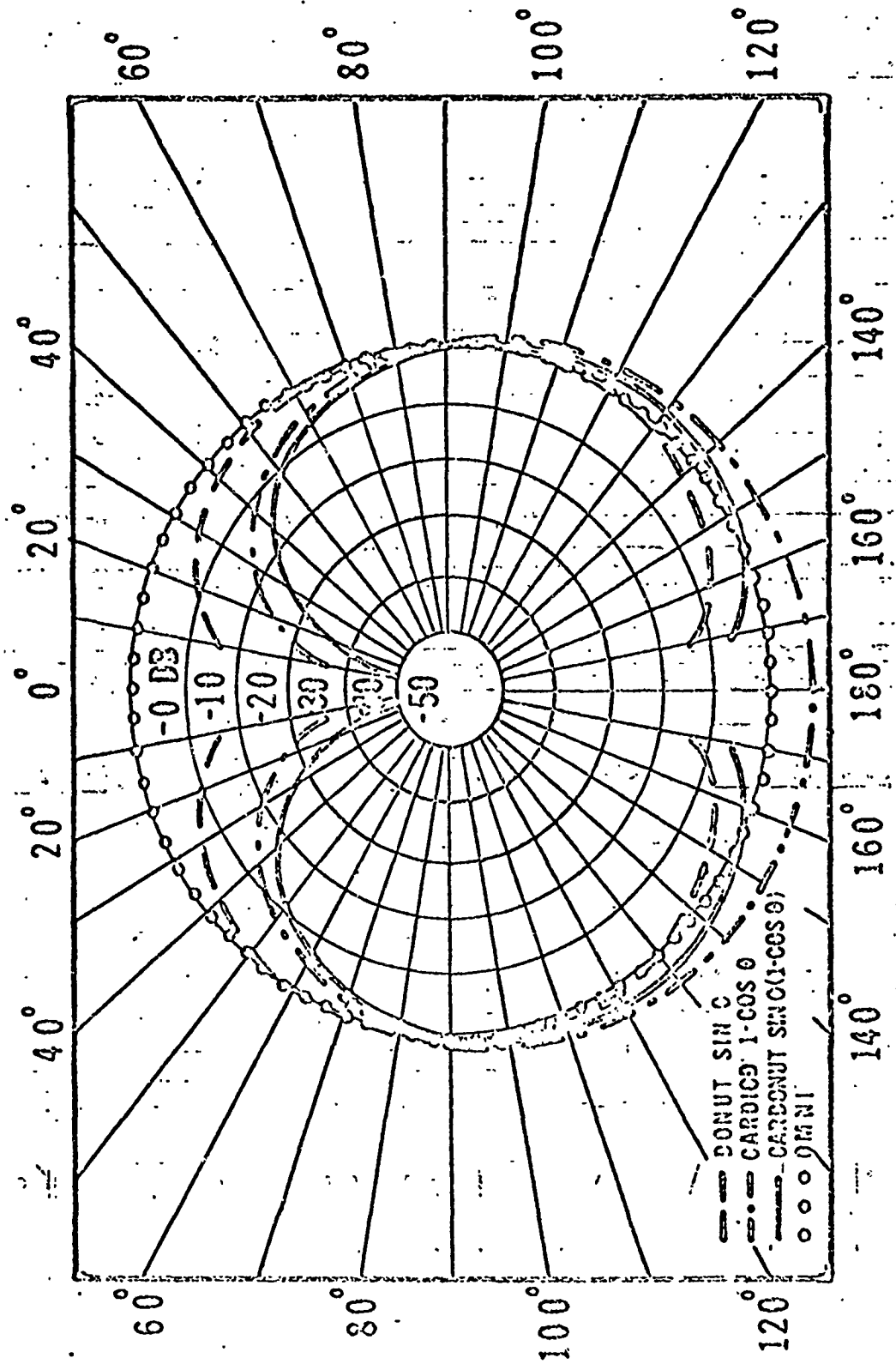
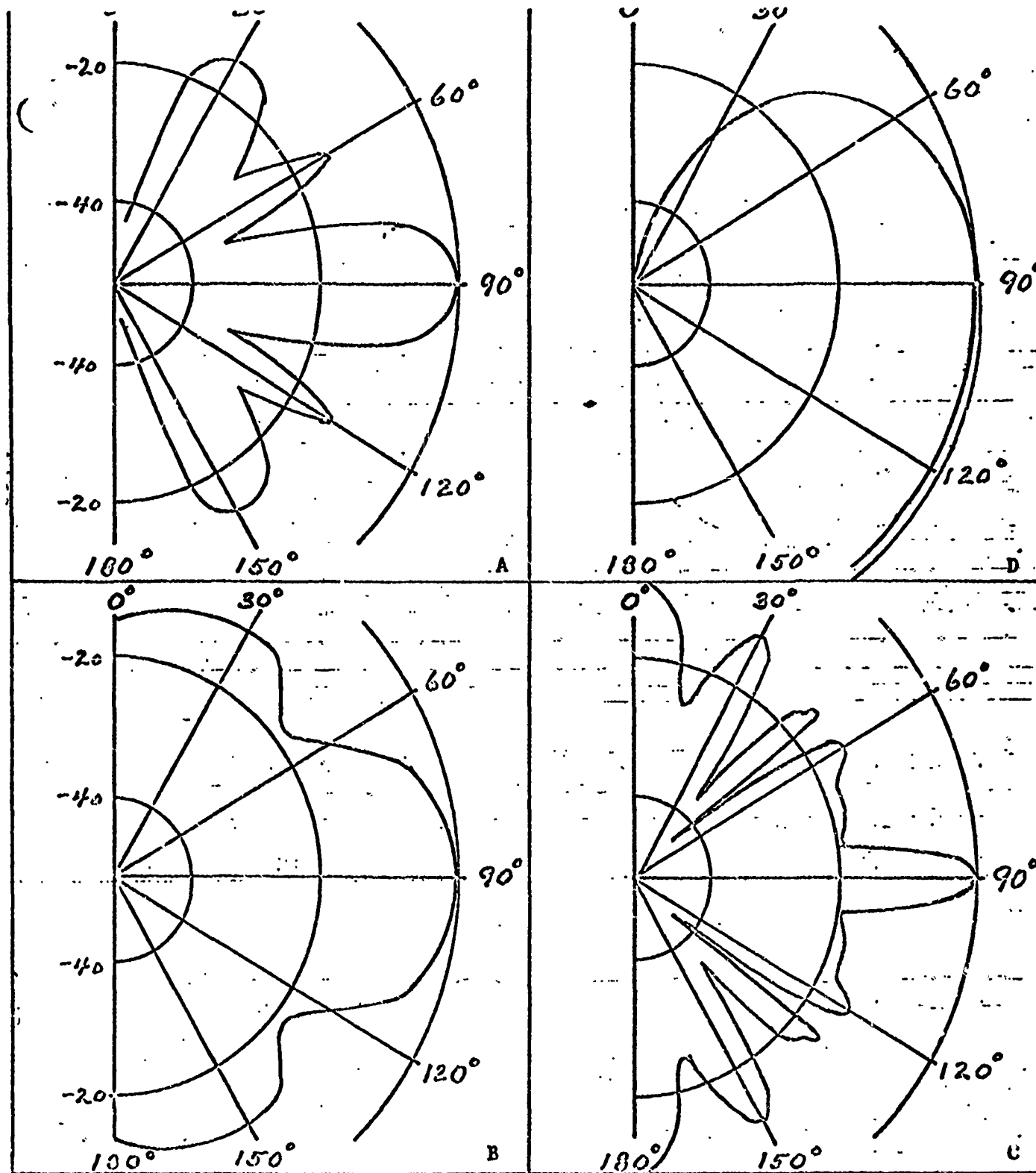


FIGURE 1



Polar response of microphone arrays.

A, B, C - 6 element line array with  $\lambda/2$  uniform spacing at 89 Hz.

A - 89 Hz

B - 50 Hz

C - 150 Hz

D - CARDONUT

APPENDIX B

Excerpts from Spectrum Analyzer Operator Training Manual,  
NADC Report No. NADC-SD-6912, 14 Feb. 1969, Unclassified

## 1. GENERAL

This manual is intended for use by operators working with the Naval Air Development Center Spectrum Analysis System. It is a basic information manual discussing in common language the problems of acoustic signature analysis. Included is the knowledge required by the Spectrum Analyzer Operator (SAO) to elevate his understanding to the level of a signature analyst.

The SAO studying this lesson is assumed to have completed the three lessons of the training course covering pattern recognition. It is also assumed that the SAO's operational experience has sufficiently reinforced the knowledge presented in the pattern recognition course to justify attaching the problems associated with signature analysis.

One of the questions that an SAO has probably considered while observing the expert operator using the system is:

How can the expert state that the signature is,

- a. a 4-cylinder, 2 cycle engine,
- b. an 8-cylinder engine,
- c. helicopter with 4 blades,
- d. three-bladed turbo prop aircraft,
- e. two six-cylinder trucks.

The primary facts which must be considered in signature analysis are:

- a. Every line appearing in a signature means something.
- b. Relative intensity of lines is of significant value and must be considered.
- c. More than one line must be visible to realistically classify an acoustic sound source.

The SAO has learned from the previous lessons how to recognize and classify major categories as aircraft or ground vehicle. The basic criteria used in this process is an evaluation

of the frequency stability, or instability, of the lines appearing from a given sound source. If a line exhibits good stability and varies in a slow smooth fashion, the SAO has been instructed to recognize this pattern as an aircraft with doppler effect causing the frequency shift. While a pattern of this fashion is being displayed, the SAO could listen to the sound and expect to hear an approaching aircraft that would then pass over the sensor and depart. This doppler shift pattern is very common to aircraft and consequently is a major classification clue. If a group of lines are very unstable and deviate through large frequency increments, the SAO has been instructed to recognize the deviation pattern as characteristic of a ground vehicle. This information is of significant value in the classification process, but not necessarily the only information available. When the SAO has learned to see all the lines and recognize the detailed characteristics of these lines, he will then be able to make significant judgments concerning the acoustic signal source. For example, rather than a simple (though important) classification of ground vehicles vs aircraft, the SAO will be able to state a discrete number of vehicles and possibly vehicle types. The analysis function is normally a time consuming operator task, but as an operator learns to automatically recognize the cues he will be able to respond rapidly and will be able to classify the acoustic signal source more accurately.

A fact presented earlier indicated that, "more than one line must be visible to realistically classify an acoustic sound source". An explanation of this statement is very logical. For instance, if a ground vehicle was passing a sensor and only one line was displayed, then it would be impossible to determine where the line (sound) was generated in the vehicle. Some of the possible sources could be:

- |                 |                |
|-----------------|----------------|
| a. engine       | e. horn        |
| b. transmission | f. tire rumble |
| c. rear end     | g. brakes      |
| d. body sound   |                |



Without knowing this actual vehicle it would be impossible to determine from a one line signature where the sound was being generated.

The SAO must understand that the example stated above is theoretical in the sense that it is very difficult if not impossible for an engine-driven piece of machinery to produce a clean harmonic free frequency which would only produce one signature line. The normal case with engine-powered vehicles, both air and ground, is the production of harmonically related lines. The power trains produce definite discrete signatures, but they are seldom pure in tonal quality. They normally are very rich in harmonic content.

## 2. HARMONICALLY RELATED LINES

"Harmonic content" is a phrase which describes a group of frequencies made up of a basic fundamental frequency and the exact multiples of the fundamental. A fundamental and its harmonics form a harmonic series. Unless affected by other phenomena, the fundamental frequency of a harmonic series will be the strongest, and the energy contained in each of the harmonics varies inversely as the number of that harmonic. Figure 1 depicts a harmonic series with a frequency change at the fundamental frequency and the resultant effect as the harmonically related change.

To summarize, certain facts must be understood about a harmonic series to facilitate analysis of the data presented. These facts are:

- a. All lines presented in a harmonic series must be whole number multiples of the fundamental frequency.
- b. The fundamental frequency will normally be the strongest frequency in a series and the energy contained in the harmonics varies inversely as the number of that harmonic.

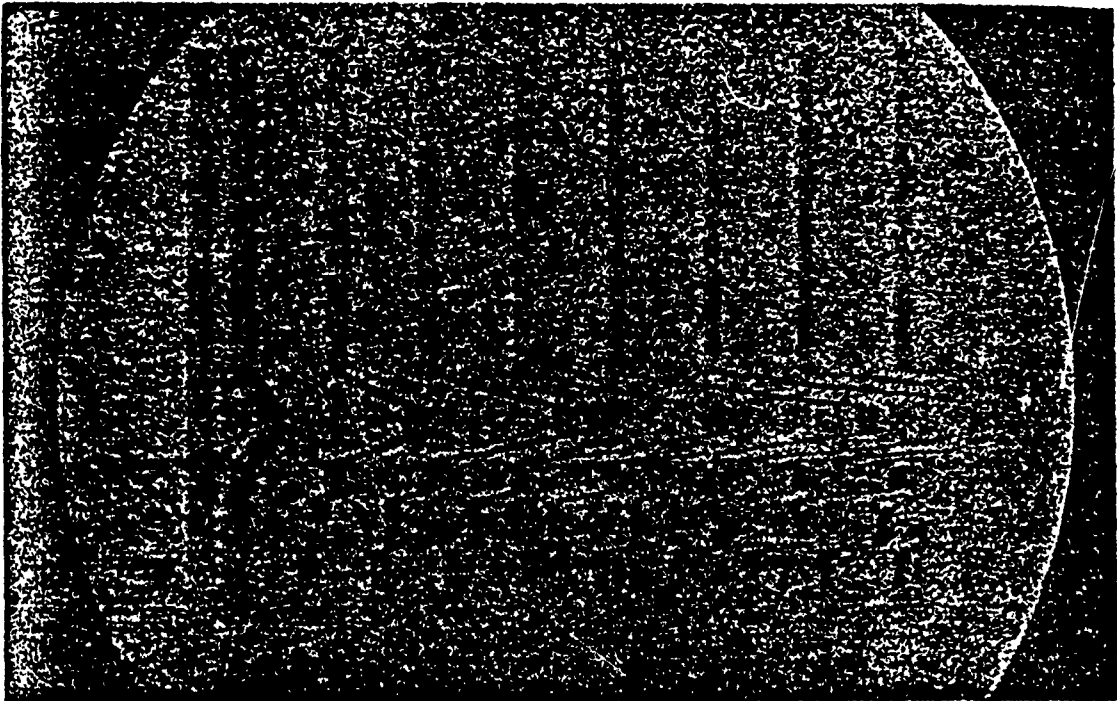


Figure 1. Harmonic Series

c. Any deviation which occurs with the fundamental frequency will occur simultaneously with the harmonics. For instance, if a 10 Hz fundamental shifted to 15 Hz in 5 seconds, then the second harmonic of 20 Hz would shift to 30 Hz in the same 5 seconds. The third harmonic of 30 Hz would shift to 45 Hz in 5 seconds and so on through the harmonic series.

Since we have stated that the harmonics must be whole number multiples of the fundamental frequency, you can appreciate that the fundamental frequency therefore also defines the spacing of the series. This can be seen in figure 1. We have lines of 10, 20, 30, 40, 50, 60, 70, and 80 Hz demonstrating that with a fundamental of 10 Hz we have a spacing of 10 Hz through the series. You will also note that when the fundamental was changed to 15 Hz the series expanded to a 15 Hz spacing.

Let us examine another group of lines and perform an analysis. (See figure 2.) You will detect lines at 10, 15, 30, 45, 50, 70, 75 and 90 Hz. In this particular case, we are generating two harmonic series groups with the odd order harmonics predominant. We are printing 1st (10 Hz), 3rd (30 Hz), 5th (50 Hz), 7th (70 Hz) and the 9th (90 Hz) from the "B" series. If we check to see which lines are left we will find lines at 15, 45 and 75 Hz. You will note that the second "A" series is showing a fundamental (A1) of 15 Hz with a 3rd (45 Hz) harmonic and a 5th (75 Hz) harmonic.

An examination of figure 2 during the time period when the two fundamental frequencies were changed, shows different patterns. The shapes of these patterns can be recognized, and you can follow the two harmonic series as discussed above.

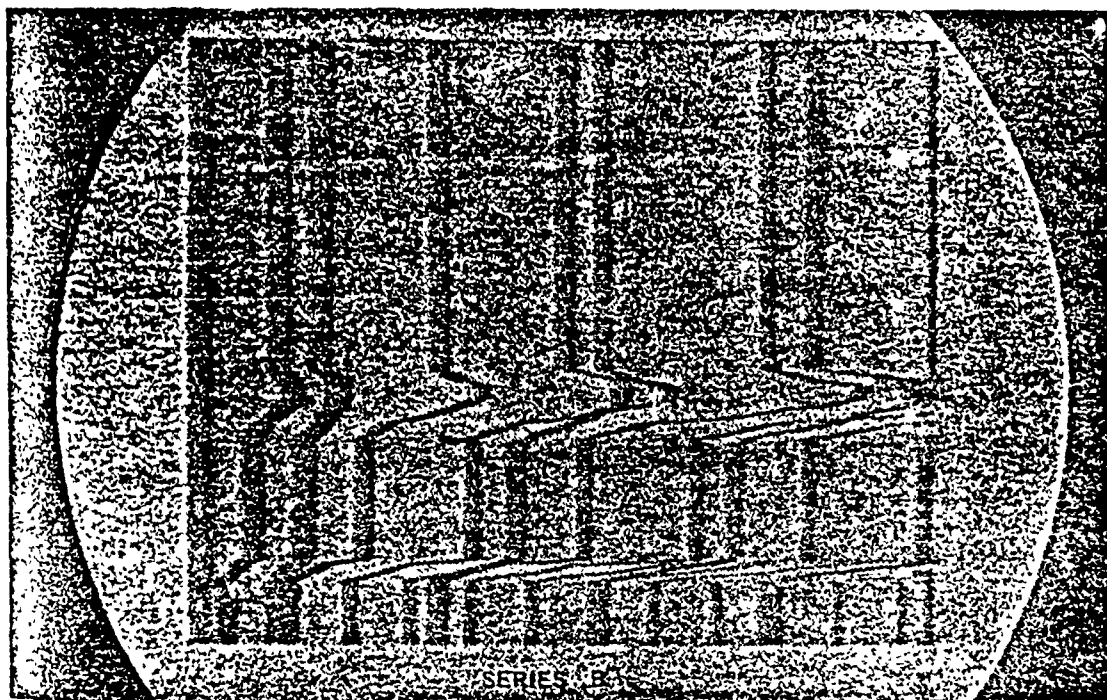


Figure 2. Two Related Harmonic Series

We have not demonstrated an example of multiple harmonic series reinforcement, but this is shown pictorially in figure 3.

You will notice that series A consists of a fundamental of 10 Hz with the 1st, 2nd, 3rd, 4th, 5th, 6th, 7th, 8th, 9th and 10th harmonics. Series B consists of a fundamental of 25 Hz with the 1st, 2nd, 3rd, and 4th harmonics. Series C consists of a fundamental of 15 Hz with the 1st, 2nd, 3rd, 4th, 5th and 6th harmonics. These three harmonic series groups have been summed and the figure indicates the relative intensity of the resultant lines. You will note that the strongest line is now the 3rd harmonic of group A reinforced by the 2nd harmonic of group C occurring at 30 Hz. This example should demonstrate the possible situation where the fundamental frequencies from a complex signature may be smaller than other given lines due to the reinforcement characteristics of multiple harmonic series groups.

### 3. MECHANICALLY RELATED LINES

In the process of performing an analytical classification you will probably find cases where lines will appear to track exceptionally well and any deviation in the basic series will be reproduced at all lines. However, there are lines appearing which are not numerical multiples within the signature pattern. This situation is normal with A/C and ground vehicles when you consider gear ratios. This situation is best described by the following example. Suppose we had a piston powered helicopter presenting a signature from its engine. The main rotor and tail rotor are driven through gear boxes. If the ratio through the two gear boxes is not exactly the same, then the two propellers will present different signatures and unless the engine to rotor gear ratio is 1:1, we would have a third set of signature lines from the engine. You will understand that if the pilot of this vehicle were to make a throttle change, we would see a deviation in the engine signature and simultaneously in the signature presented by the main and tail rotors. All lines in this complex signature will deviate at the

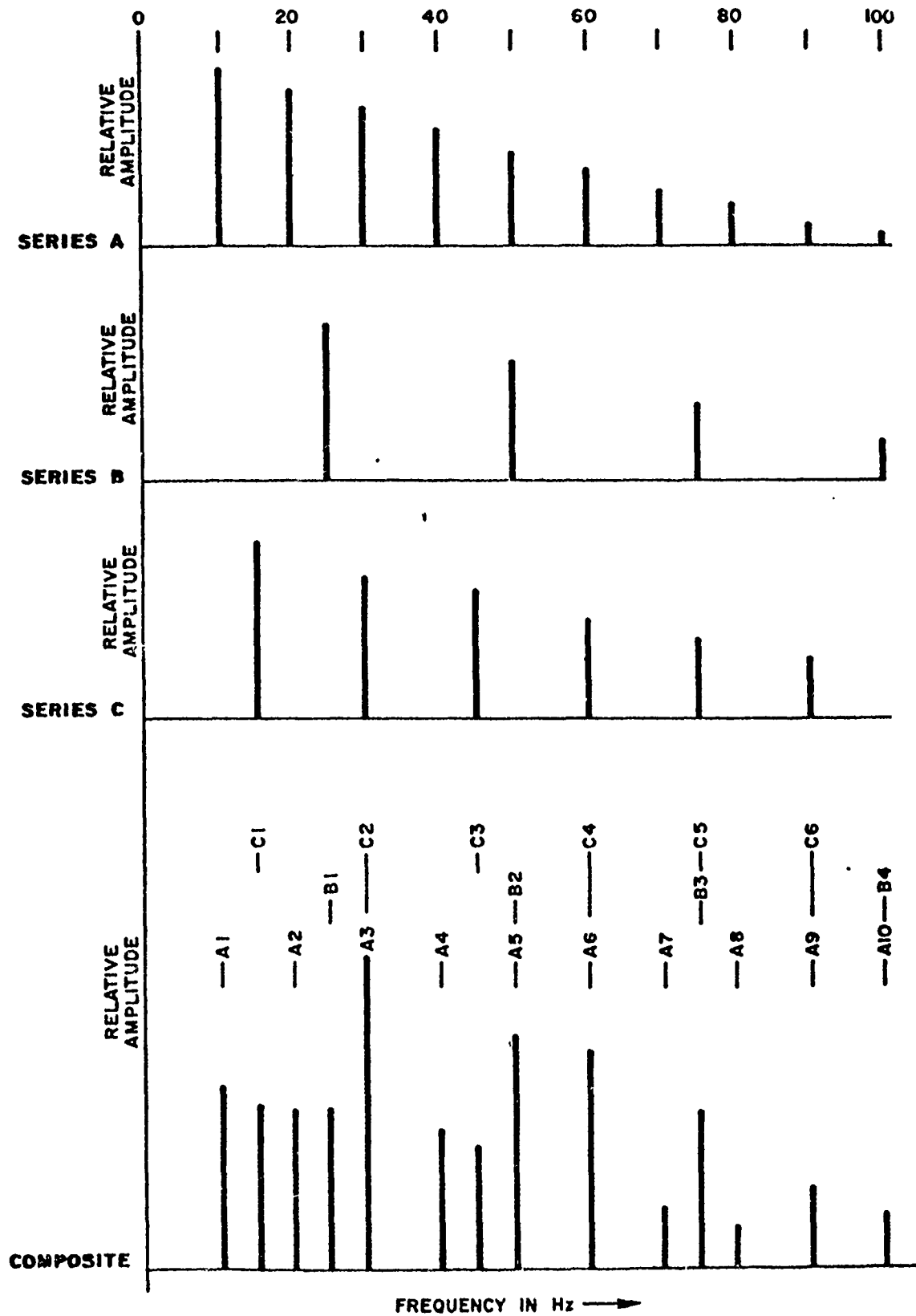


Figure 3. Multiple Harmonic Series Reinforcement

same time, and there is a mathematical relationship between various lines, but there will actually be several harmonic series of lines present.

Note figure 4, you will find a pictorial presentation of the mechanically related line situation with the "A" series starting at 10 Hz spacing and the "B" series starting at 9 Hz spacing. As the "A" series deviates to a 20 Hz series, you can see that the "B" series is tracking simultaneously to an 18 Hz series. Obviously to have a relationship such as used in the example, we would require a gear ratio of 0.9 to 1, reference B to A.

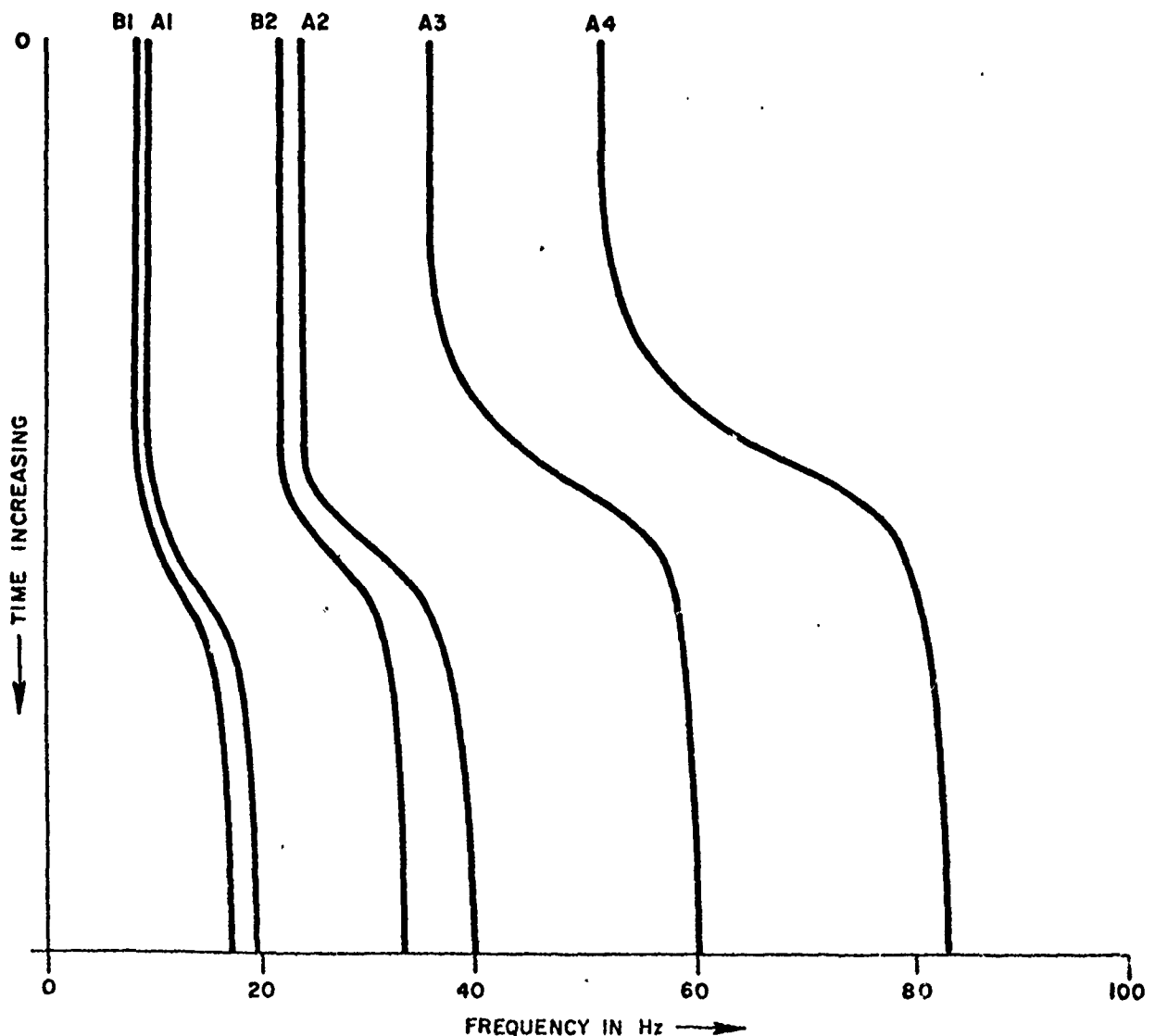


Figure 4. Mechanically Related Lines  
B to A ratio = 0.9 to 1

#### 4. DOPPLER SHIFT

The pattern recognition portion of the training program introduced the SAO to the subject of classification. Lesson No. 1 presented instructions on how to operate the system and how to interpret the data printed on the display. Also included in lesson No. 1 was a simplified description of doppler shift. This subject was included since it is imperative, when classifying aircraft, that the SAO recognize certain deviation characteristics about the lines printed on the display, since the primary clue to aircraft pattern recognition is the smooth pitch change (downward shift of frequency) as the aircraft approaches, passes and moves away from the sensor.

This pitch change as a function of Rate of Change of Range (Range Rate), is a phenomenon called doppler effect and the degree of change is called doppler shift.

The doppler effect is the phenomenon evidenced by the change in the observed frequency of a wave in a transmission system, caused by a time rate of change in the effective length of the path of travel, between the source and the point of observation.

The effect is described quantitatively by

$$f_R = \frac{1 + V_{R/C}}{1 - V_{S/C}} = f_S$$

where  $f_R$  = observed frequency

$f_S$  = frequency at source

$V_R$  = component of velocity (relative to the medium) of observation point toward source

$V_S$  = component of velocity (relative to the medium) of source toward observation point

$C$  = speed of sound in a stationary medium

From this formula we can now compute the observed frequency at the sensor from an aircraft. We will present a simple

case using an aircraft traveling at a velocity of approximately 25% x the speed of sound. The following velocity factors will be assumed.

a. The speed of sound in air at sea level we will state is 1150 feet/second.

$$1150 \text{ ft/sec} = 690 \text{ knots}$$

b. If an aircraft were approaching a sensor at 172 knots, then his velocity in ft per second would be:

$$\frac{172 \text{ knots} \times 6000}{3600} = 287 \text{ ft/sec}$$

(Note: We will assume this is 25% speed of sound.)

We can now assume a sound source generating a 100 Hz tone with no velocity vector. This tone would generate a wave pattern with a repetition period of 0.01 seconds. (See figure 5.)

$$100 \text{ Hz} = 1 \text{ second}$$

$$1 \text{ Hz} = \frac{1}{100} \text{ or } 0.01 \text{ seconds}$$

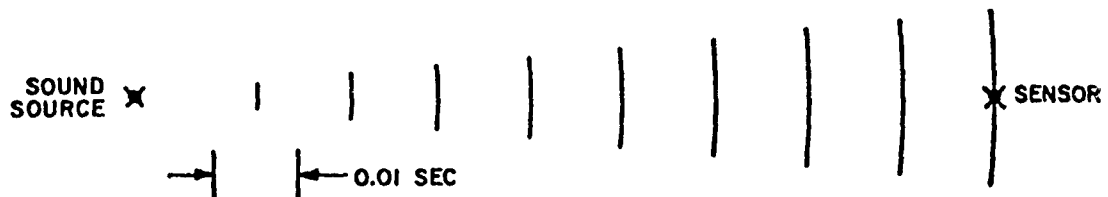


Figure 5. Repetition Period of 100 Hz Sound Wave

With a spectrum analyzer connected to the transducer at the sensor, this wave front with a repetition period of 0.01 seconds, would present a single line on the display of 100 Hz.

If we should now assume that the sound source is the aircraft defined above, with a closing range rate of 25% x speed of sound, using the same 100 Hz tone generated from the sound source



(now the aircraft) with a repetition period of 0.01 seconds, we would have to compress the wave period by 25% as a function of the velocity of the aircraft. (See figure 6.)

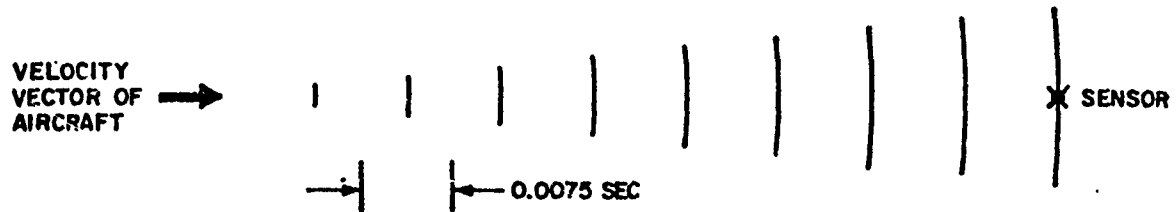


Figure 6. Repetition Period of a Compressed 100 Hz Wave

The resultant compressed wave pattern would have a repetition period at the sensor of 0.0075 sec and when a sound with this repetition period is spectrum analyzed, we would find a single line printed on our display of  $\frac{1}{0.0075} = 133 \text{ Hz}$ .

From the formula presented above, we would have:

$$f_R = ?$$

$$f_S = 100 \text{ Hz}$$

$$V_R = 0$$

$$V/S = 0.25$$

$$C = 1$$

Therefore, 
$$f_R = \frac{1 + \frac{0}{1}}{1 - \frac{0.25}{1}} \times 100$$

$$\text{or } f_R = \frac{1}{0.75} \times 100$$

$$\text{or } f_R = 1.33 \times 100$$

$$f_R = 133 \text{ Hz}$$

Continuing with this example, as the aircraft passes through minimum range to the sensor, the spectral sound will drop

in pitch and as the aircraft increases range rate (going away), the wave pattern shown in figure 7 will exist.

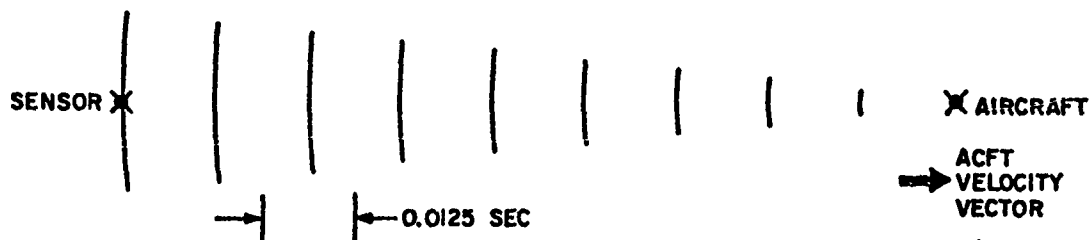


Figure 7. Repetition Period of an Expanded 100 Hz Wave

At this time the velocity vector of the aircraft will appear to expand the time between respective waves of the 100 Hz emitted sounds by 25%.

This will result in the 100 Hz wave, whose normal repetition period is 0.01 seconds, now appearing with a repetition period at the sensor of 0.0125 seconds and when analyzed, will appear on the display as a single line located at  $\frac{1}{0.0125} = 80$  Hz.

From the formula for doppler effect, we would have:

$$f_R = ?$$

$$f_S = 100 \text{ Hz}$$

$$V_R = 0$$

$$V_S = -0.25$$

$$C = 1$$

Therefore

$$f_R = \frac{1 + \frac{0}{1}}{1 - \frac{-0.25}{1}} \times 100$$

or

$$f_R = \frac{1}{1.25} \times 100$$

$$f_R = 0.8 \times 100$$

$$f_R = 80 \text{ Hz}$$

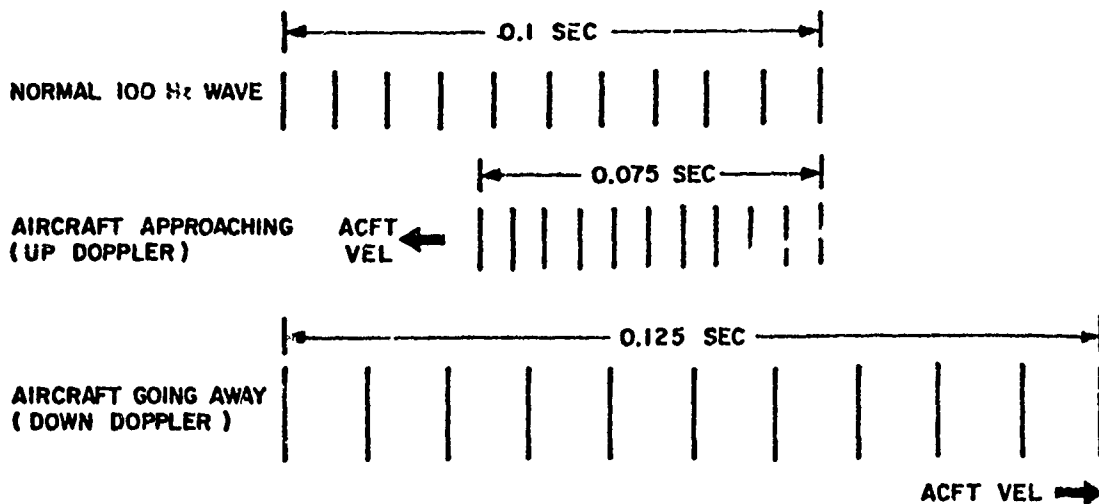


Figure 8. Composite of Normal, Compressed and Expanded 100 Hz Waves

The above plot (figure 8) shows the time for 10 Hz of the respective waves discussed in the previous write up.

The normal 100 Hz wave has a repetition rate of 0.01 sec x 10 waves = 0.1 seconds.

The compressed wave has a repetition rate of 0.0075 sec x 10 waves = 0.075 seconds.

The expanded wave has a repetition rate of 0.0125 sec x 10 waves = 0.125 seconds.

The frequency will convert as follows:

$$f = \frac{1}{\text{wave period}}$$

$$f = \frac{1}{0.01} = 100 \text{ Hz}$$

$$f = \frac{1}{0.0075} = 133 \text{ Hz}$$

$$f = \frac{1}{0.0125} = 80 \text{ Hz}$$

See figures 9 and 10 for pictorial and photographic display of the effects of the doppler phenomenon.

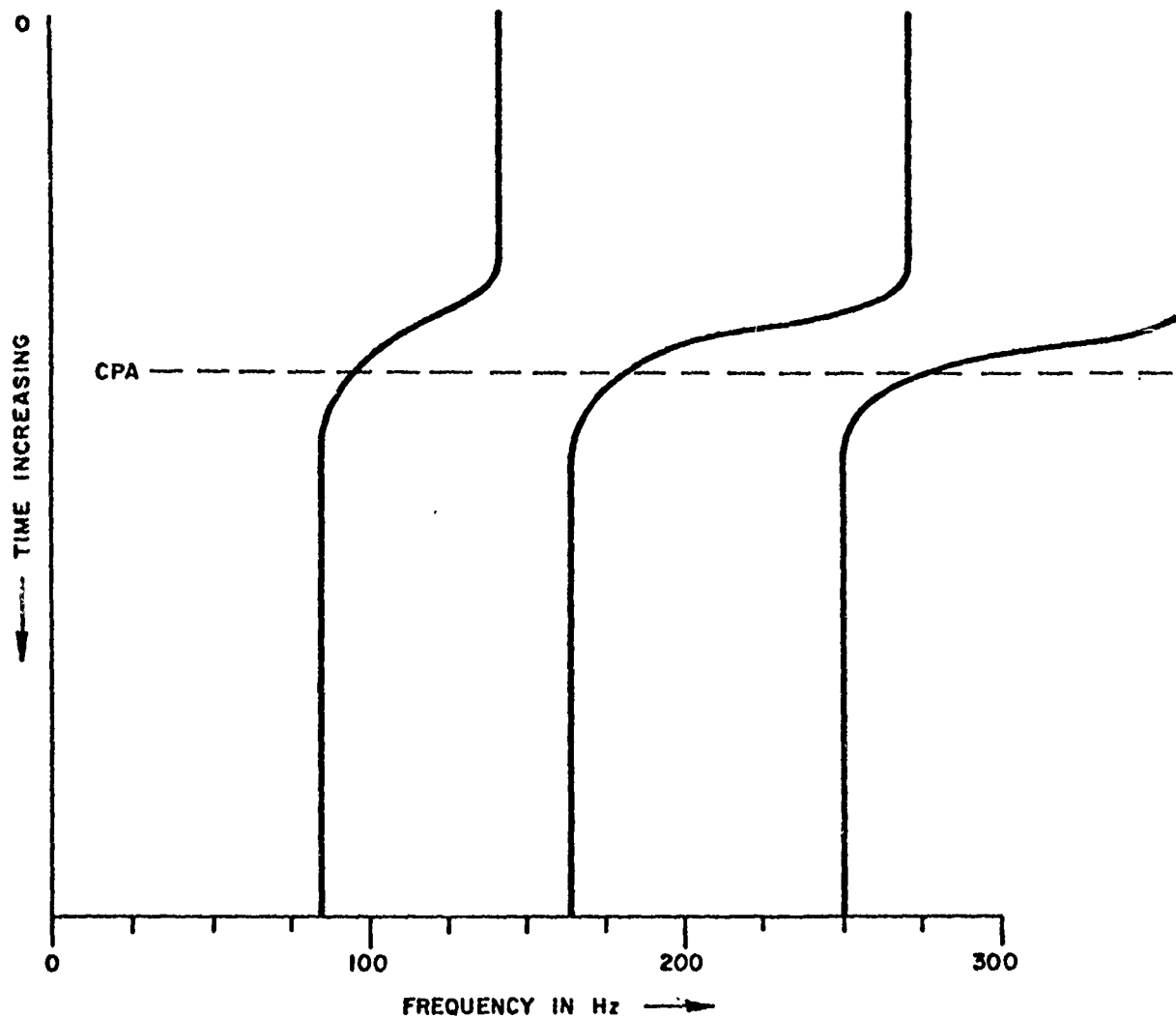


Figure 9. Pictorial Presentation of Doppler Shift of Frequency for an Aircraft Generating a 100 Hz Fundamental Frequency

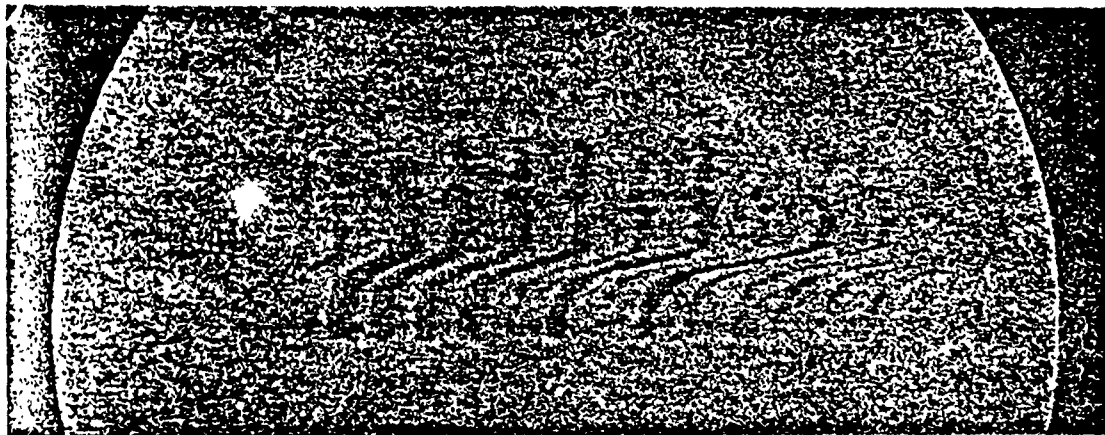


Figure 10. Signature of Doppler Shift

## 5. SOUND ORIGINS

### a. Ground Vehicle

The primary source of sound energy from a ground vehicle will be from the engine. There are other sounds generated such as: body rattles, tire rumble, etc., but these sounds are very low in amplitude compared with the energy emanating from the engine and power train of a loaded truck. (See figure 11.)

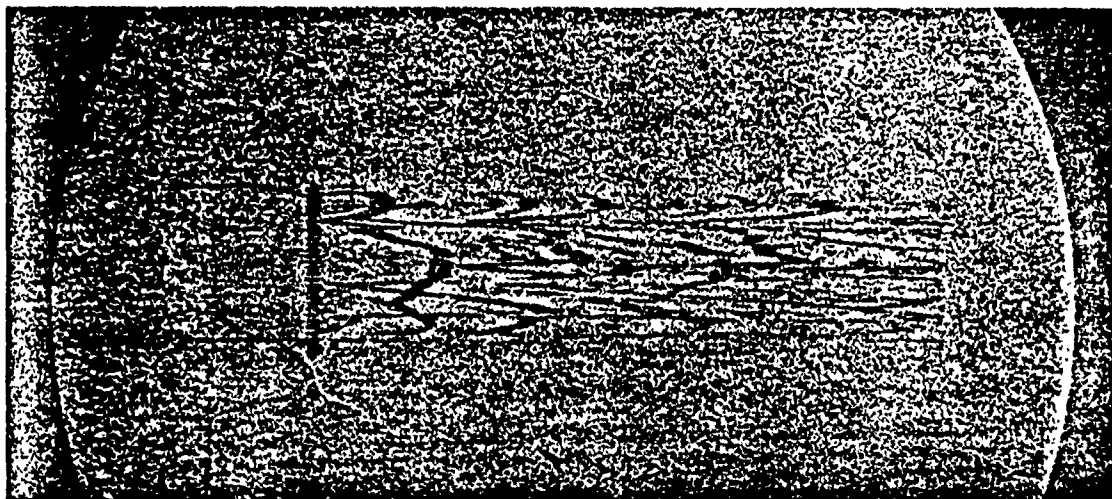


Figure 11. Signature of Ground Vehicle

### b. Piston Powered Aircraft

In the case of a piston powered aircraft, we have the engine generating sound and the propeller generating sound, but the propellers usually present a much stronger signature.

With aircraft, we must contend with the doppler effects at all times. Therefore, the operator will have to consider the relative movement of an aircraft at any time that he is analyzing an A/C signature. (See figure 12.)

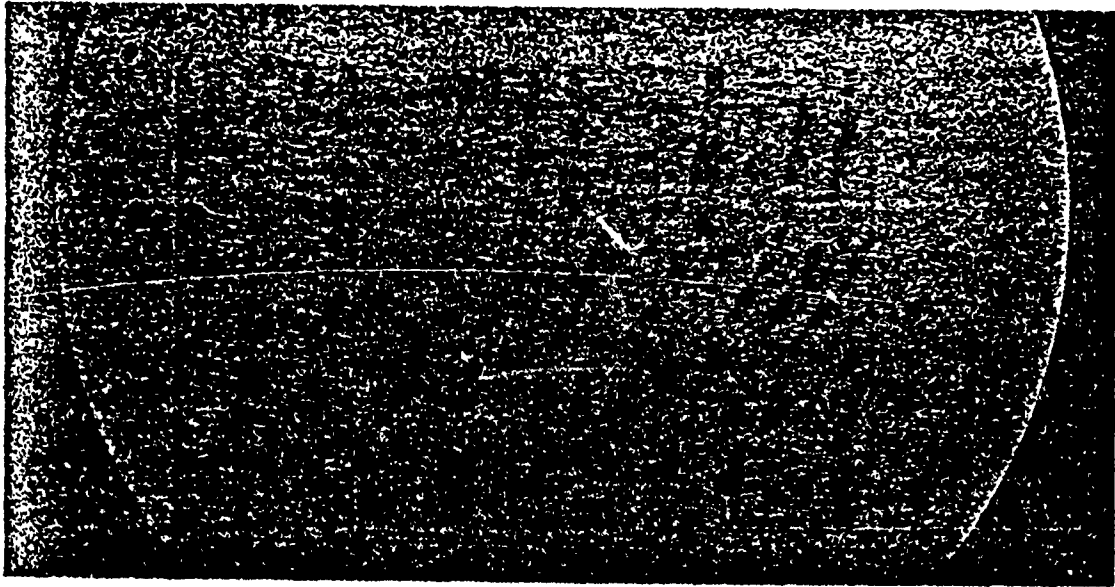


Figure 12. Signature of Piston Powered Aircraft

c. Turbo Prop Aircraft

The sound generated by a turbo prop aircraft is usually a propeller pattern, and when the range to the sensor is short, the broad band noise pattern from the jet engine will appear in the signature. (See figures 13 and 14.)

d. Jet Aircraft

The sounds emitted by a jet powered aircraft are broad band in nature and do not normally present any discrete lines. The signature of a jet aircraft can best be described as a finger print pattern showing swirls of broad diffuse lines. The broad band patterns usually appear to be decreasing in frequency as the jet is approaching the sensor. The pattern generally shows a minimum frequency when the jet is at CPA (Closest Point of Approach). As the jet is increasing range (going away) the broad band pattern appears to be increasing in frequency. Many theoretical reasons for this swirl pattern have been analyzed,



Figure 13. Signature of Turbine-Prop Aircraft,  
Prop Only

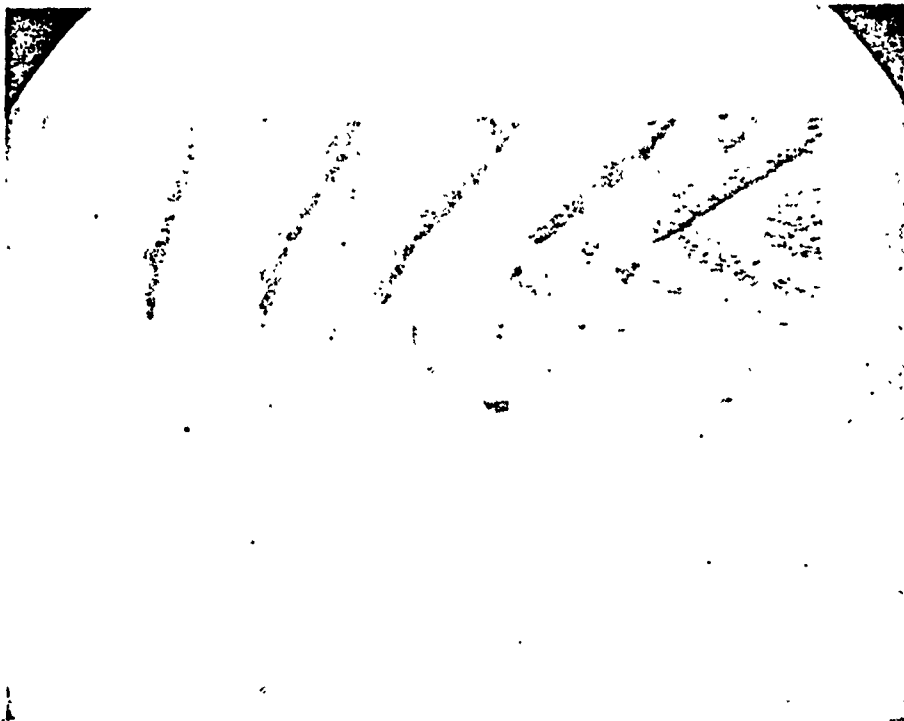


Figure 14. Signature of Turbine-Prop Aircraft  
Including Jet Sound

but no logical conclusion has as yet been reached. The most acceptable description of this pattern, at the present time, indicates that the sound varies with the aspect angle of the jet. This translates simply that there is one type of broad band noise generated at the intake of the engine, another at each of the turbine stages and combination chamber, and another generated from the exhaust. Depending upon the angle of your position to the aircraft there is a broad band beat frequency between these sound sources. As the aircraft (jet) flies over the sensor, the aspect angle will be changing at a rapid rate and this gives the broad band swirl pattern. (See figure 15.)

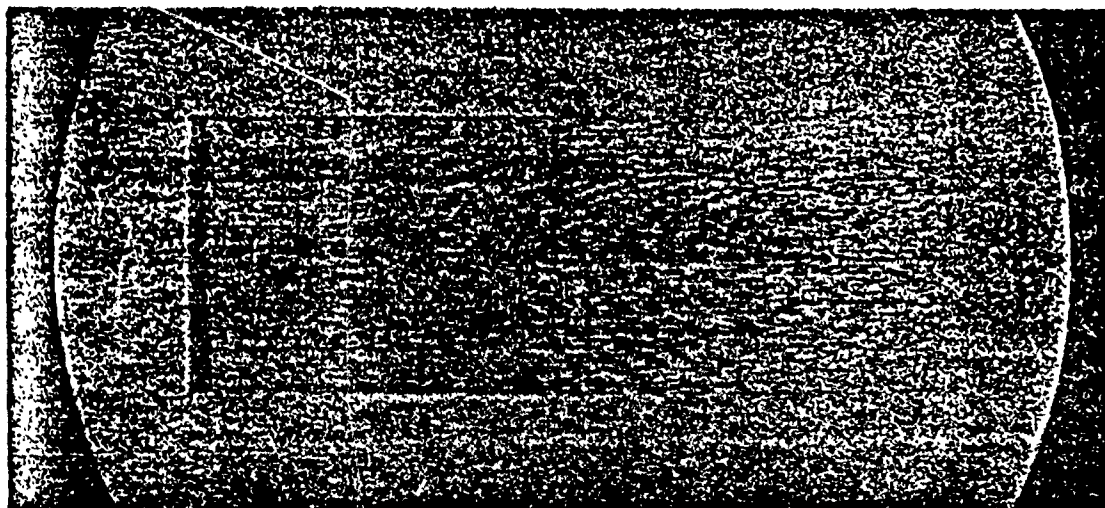


Figure 15. Signature of Jet Aircraft

#### 6. SIGNATURE ANALYSIS

A signature is the combination of discrete frequencies that identify one target from another. The signal components that make up a target signature may be from a single source or from a combination of sources. The major sources of discrete frequencies used for spectrum analysis of aircraft are:



- a. propeller shaft rate (S)
- b. propeller blade rate (B)
- c. engine

The major sources of discrete frequencies used for spectrum analysis of ground vehicles are:

- a. crank shaft rate (CSR)
- b. cylinder rate (CR)
- c. engine firing rate (EFR)
- d. auxiliary lines

As would be expected, these identifying sound sources are all associated with the respective propulsion systems. Each of these sound sources is discussed in the following paragraphs.

a. Propeller Sources

There are two fundamental frequencies associated with the sound output of an aircraft's propeller. The lower of these frequencies occurs at the rotation rate of the propeller shaft and the higher occurs at the propeller blade rate.

- (1) Propeller Shaft Rate. The fundamental frequency of the shaft sound is determined by the shaft rate. The shaft rate, which is naturally a function of the shaft's RPM is determined as follows:

$$S \text{ (shaft rate)} = \frac{\text{RPM}}{60}$$

The generation of this fundamental frequency may be caused by a nicked blade, out of balance propeller, noisy shaft bearings, etc., or a combination of these. Figure 16 illustrates the impractical condition of a one-bladed propeller. In this condition all sound output would be at the fundamental frequency ( $S_1$ ) and at the harmonics ( $S_2$ - $S_{10}$ ) of the shaft rate.

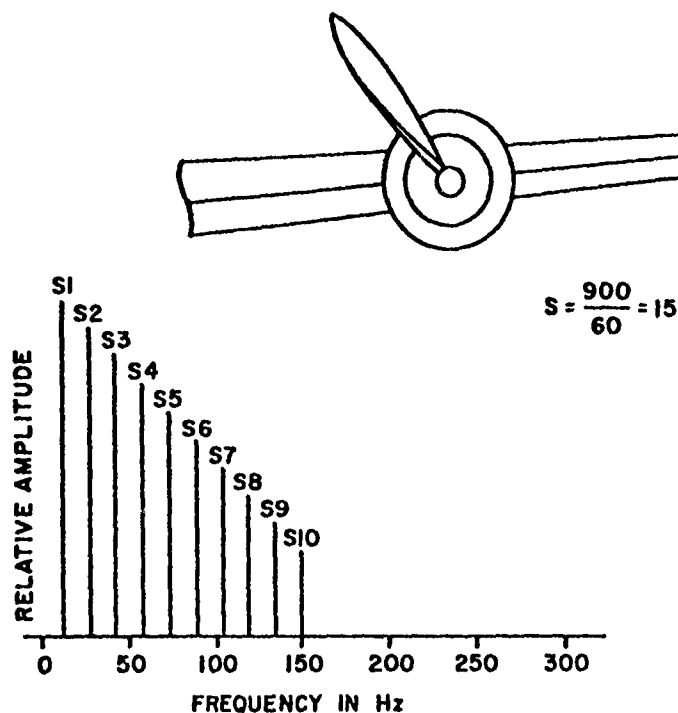


Figure 16. Sound Spectrum of a One-Bladed Propeller

- (2) Propeller Blade Rate. The greatest portion of an aircraft signal is generated by the movement of air caused by the blades of the propeller. The fundamental frequency of this sound is a function of the propeller shaft's RPM and the number of blades on the propeller, where:

$$B(\text{blade rate}) = \frac{\text{RPM}}{60} \times \text{No. of blades or}$$

$$B = S \times \text{Number of blades.}$$

The blade fundamental frequency which is an exact multiple of the shaft rate, will reinforce those harmonics of the shaft rate divisible by the number of blades on the propeller. The propellers shown in figures 17, 18 and 19 are of a 2-bladed, 3-bladed and 4-bladed type, respectively, with their respective signatures. Note the emphasis in each signature of the blade rate fundamental ( $B_1$ ) and its harmonics ( $B_2$ - $B_5$ ).

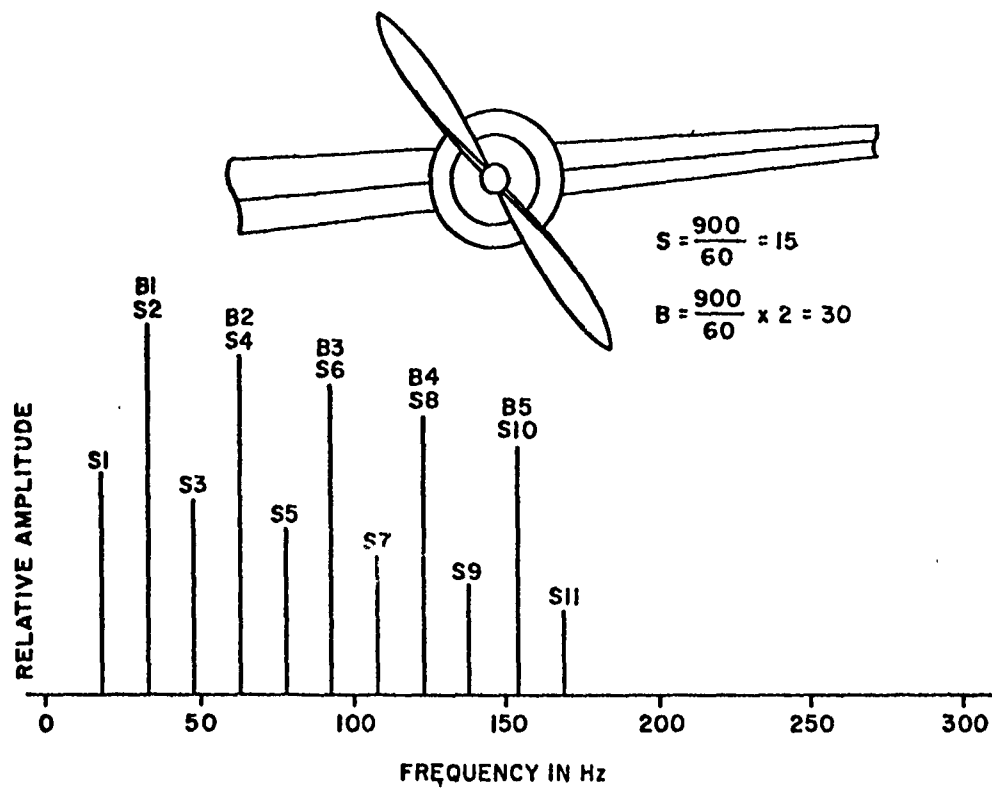


Figure 17. Sound Spectrum of a 2 Bladed Propeller

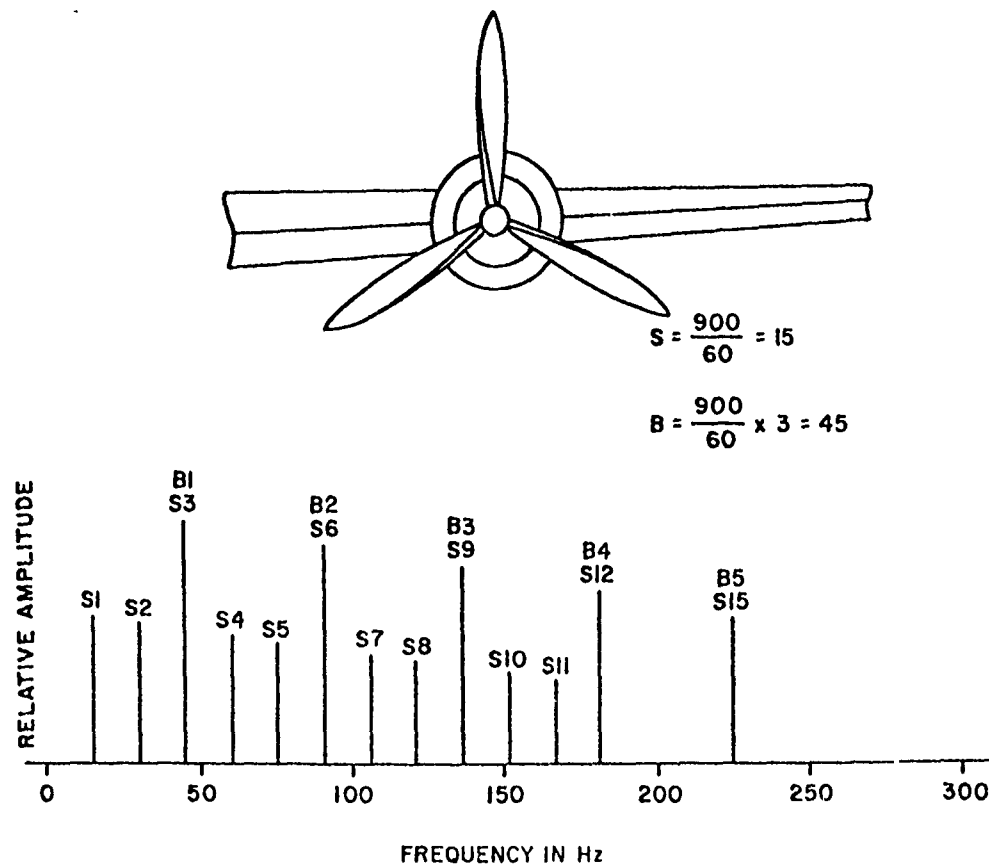


Figure 18. Sound Spectrum of a 3 Bladed Propeller

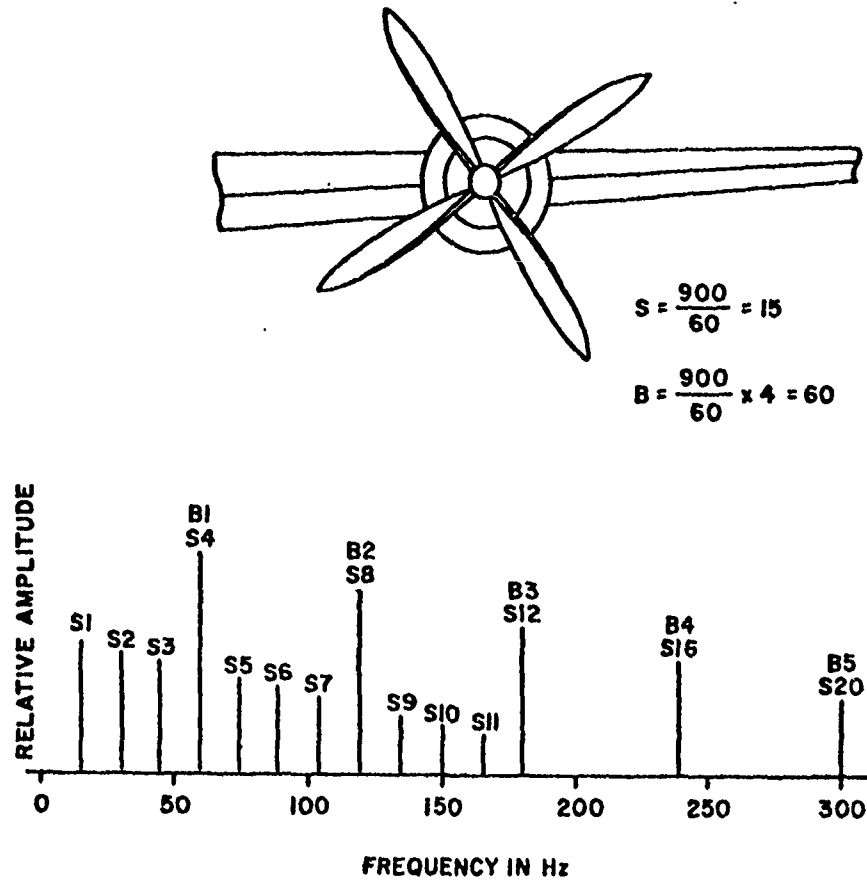


Figure 19. Sound Spectrum of a 4 Bladed Propeller

In a relatively high percentage of aircraft propeller signatures, the shaft rate component is of such low amplitude that few, if any, harmonics are detectable. In such cases, the operator must rely on his experience and the appearance of the blade lines to determine the probable number of blades on the propeller by a "best guess" method.

Multiple engine aircraft produce certain characteristics that are somewhat different from a single engine aircraft. In most cases the aircraft engines and propellers are synchronized and appear as a single engine signature. However, if a twin engine aircraft were to lose "sync", the spectral display shown in figure 20 would be the result. The lines gradually broaden until they separate into two distinct lines or "doublets".

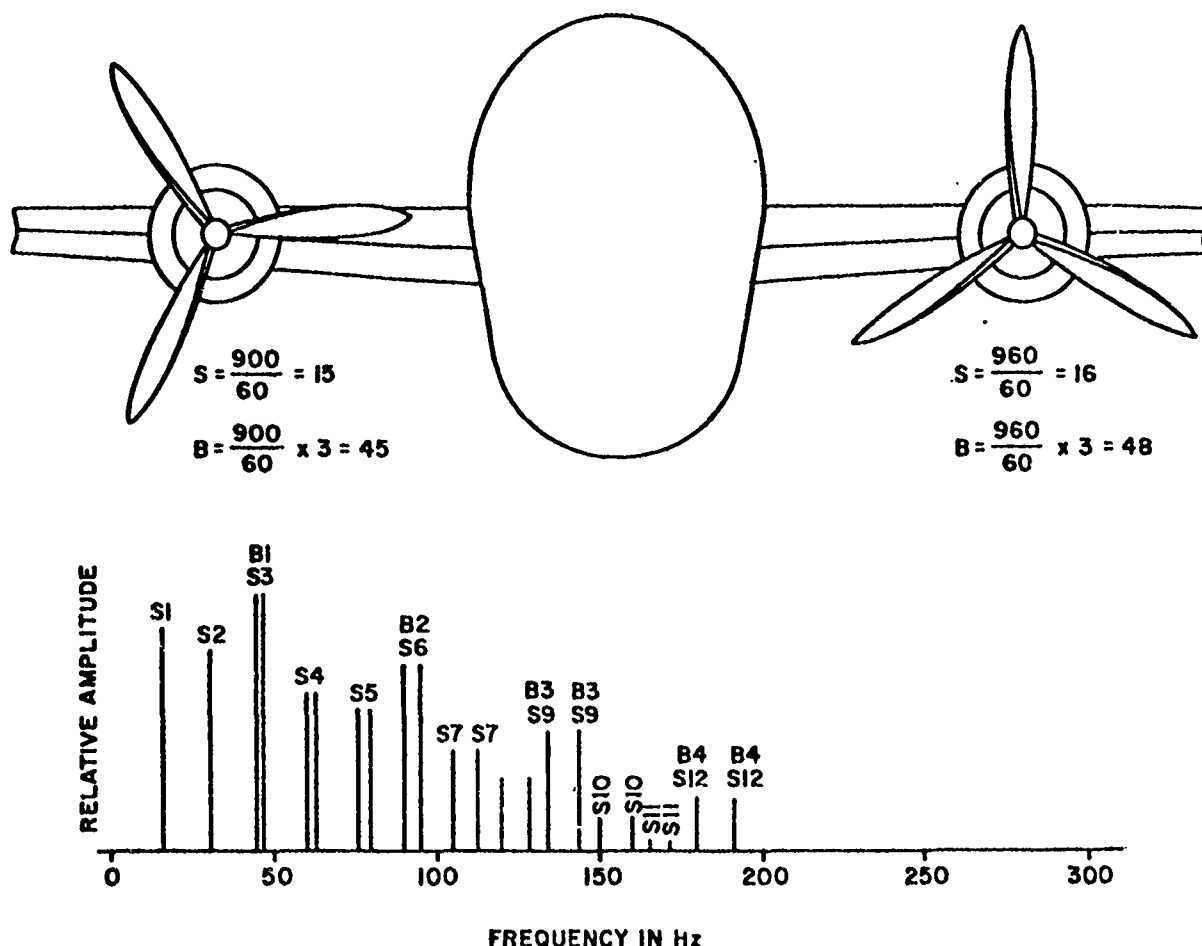


Figure 20. Twin Engine 3 Bladed Prop Aircraft  
Out of Sync

b. Engine Signatures

The most common signature source that the operator encounters is the signals generated by gasoline or diesel fueled reciprocating engines. Each type engine generates sounds that are peculiar and identifiable to reciprocating engines. Also, the two basic types of reciprocating engines (two-cycle and four-cycle) generate identifiable signatures.

c. Two-cycle engine

Use of this type of engine is limited to small gasoline engines (lawn mowers, power saws, lightweight motorcycles) and large diesel engines (locomotives, ships, submarines and some foreign ground vehicles). An understanding of the relationships between the functions of a two-cycle engine and the sound produced, however, facilitates an understanding of the more common four-cycle engine.

The two-cycle engine produces a power stroke from each cylinder for every revolution of the crank shaft. Figure 21 illustrates the two-cycle engine and its associated sound spectrum.

- (1) Crank Shaft Rate (CSR). As the crank shaft of a two-cycle engine rotates, it generates a sound whose frequency is dependent upon the engine speed:

$$CSR = \frac{RPM}{60}$$

Since 700 RPM has been assumed for the sample shown in figure 21, the CSR is 10 Hz.

- (2) Cylinder Rate (CR). With one power stroke for each revolution of the crank shaft, the cylinder firing rate (CR) is equal to the crank shaft rate CSR:

$$CR = CSR$$

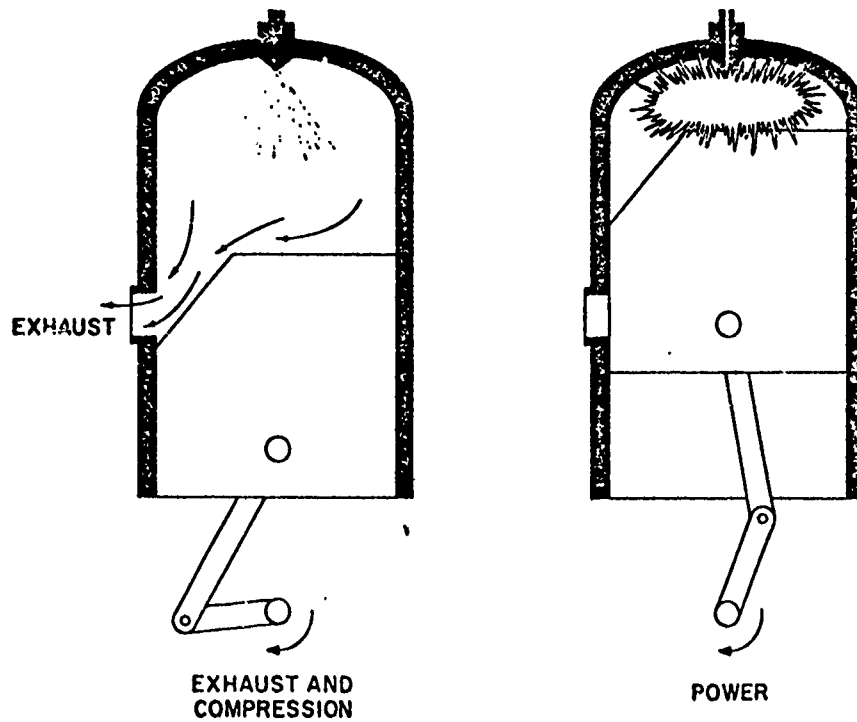
Regardless of the number of cylinders in the engine, and the fact that they each fire at a different time, they each fire at the same rate.

Since the cylinder rate and the crank shaft rate of the two-cycle engine have the same fundamental frequency, they are generally designated by an analyst as CR only on the display.

- (3) Engine Firing Rate (EFR). The third basic frequency of the engine is produced because the cylinders are not firing at the same time, and is referred to as the engine firing rate. The frequency of this signal is equal to the number of cylinders in the engine multiplied by the cylinder rate.

$$EFR = \text{No. of cylinders} \times CR$$

Since the two-cycle engine shown in figure 17 is assumed to have eight cylinders, the EFR is 80 Hz. The EFR will reinforce the eighth harmonic of the CR and should produce the strongest component of the sound spectrum of this engine.



RPM = 600  
 $CSR = \frac{RPM}{60}$   
 CSR = 10Hz

NO. OF CYLINDERS - 8

CR = CSR  
 CR = 10Hz

EFR = CR x NO. OF CYLINDERS  
 EFR = 80Hz

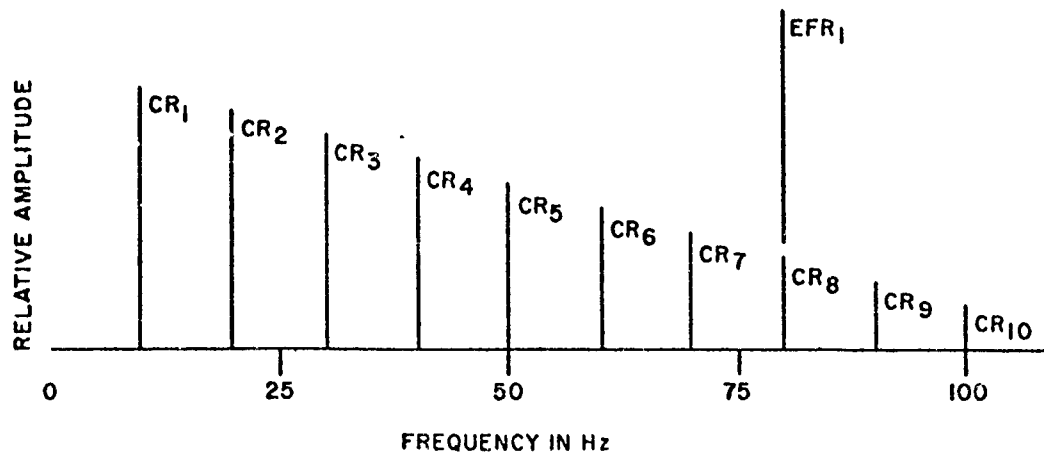


Figure 21. Sound Spectrum of a Two-Cycle Engine

In summary, the sounds generated in a two-cycle diesel or gasoline engine are the crank shaft rate (CSR), cylinder rate (CR) and the engine firing rate (EFR). The frequencies of the CSR and CR are the same and tend to reinforce each other. The EFR reinforces the harmonics of the CSR/CR equal to the number of cylinders in the engine (the 8th harmonic in the sample case). The EFR-CR reinforced signal is generally the strongest signal in a two-cycle engine signature.

d. Four-cycle Engine

The most common reciprocating engine used in ground vehicles and aircraft is the four-cycle gasoline or diesel fueled type. Unlike the two-cycle engine, the four-cycle engine does not produce a power stroke for each cylinder for every revolution of the crank shaft. The four-cycle engine requires two revolutions of the crank shaft to produce a power stroke for each cylinder. Figure 22 illustrates the operation of a four-cycle engine and its generated sound spectrum.

- (1) Crank Shaft Rate (CSR). As the crank shaft turns, a sound is generated with a fundamental frequency determined by the engine speed. This signal is denoted as the Crank Shaft Rate (CSR), where:

$$CSR = \frac{RPM}{60} \text{ in Hz}$$

Note that the engine shown in figure 22 is assumed to be operating at 600 RPM producing a fundamental CSR of 10 Hz.

- (2) Cylinder Rate (CR). As the crank shaft rotates, a second fundamental sound is generated by the four-cycle engine as a result of the cylinder firing. It must again be pointed out that in a four-cycle engine, each cylinder fires once for each two revolutions of the crank shaft, and generates a signal one-half the frequency of the crank shaft rate. This signal, referred to as cylinder rate (CR) of the engine, is computed as follows:

$$CR = \frac{CSR}{2} = \frac{RPM}{120}$$



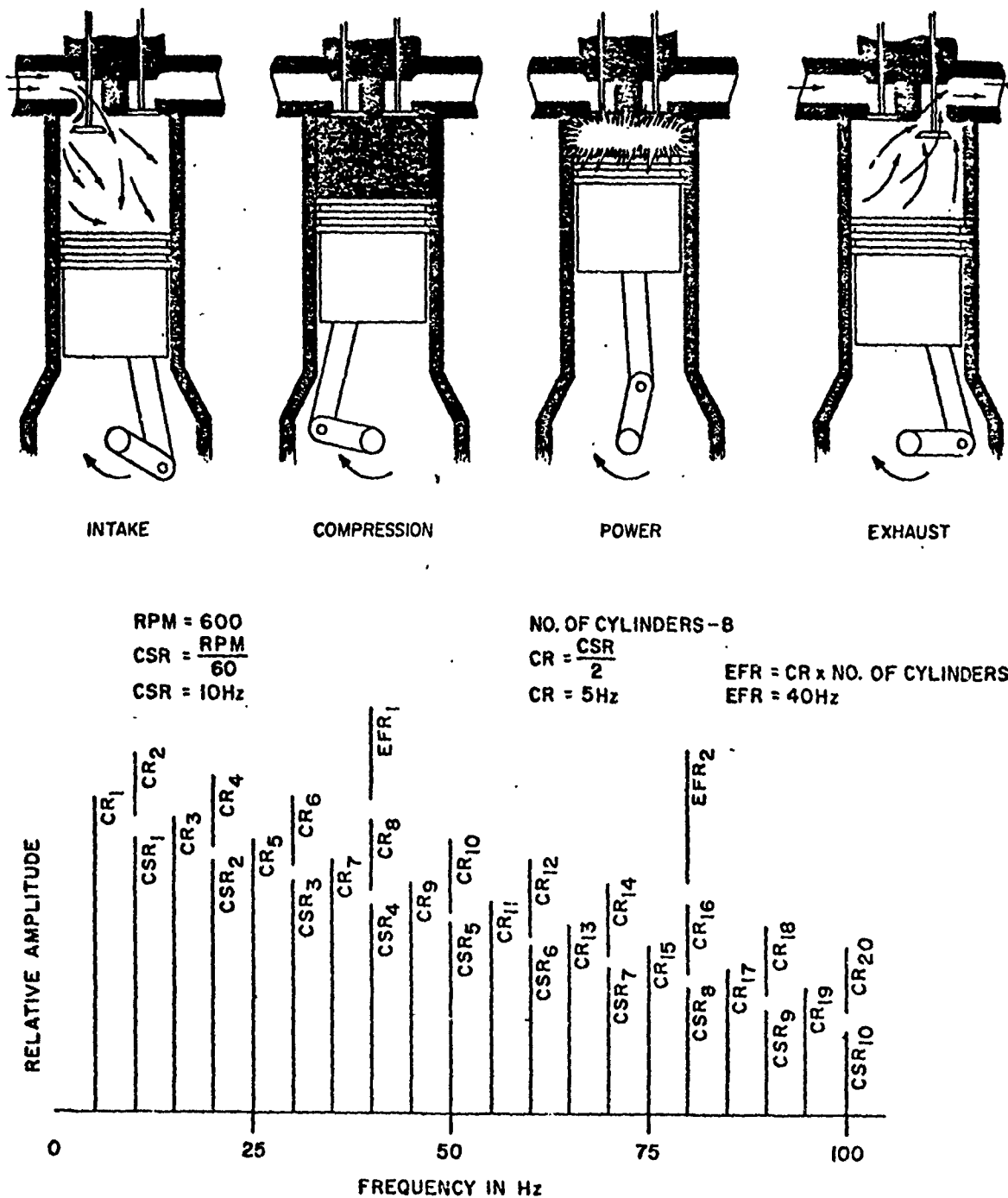


Figure 22. Sound Spectrum of a Four-Cycle Engine

From the example shown in figure 22, the CR would be 5 Hz. Two facts are readily apparent from this data:

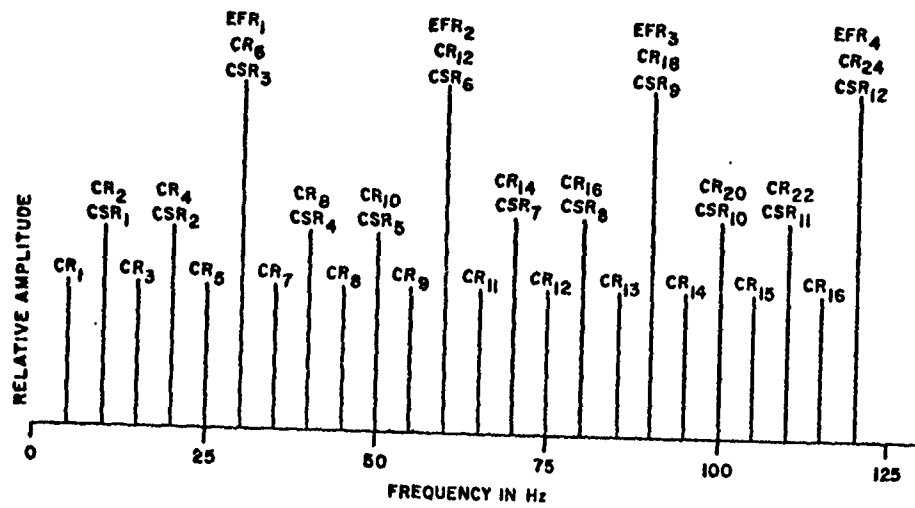
- (a) More energy is present in the CR signal than in the CSR signal.
  - (b) The CSR signals and the even harmonics of the CR signals reinforce each other.
- (3) Engine Firing Rate (EFR). The third fundamental frequency generated by the four-cycle engine is the frequency produced as a result of all cylinders firing, and is referred to as the engine firing rate (EFR). This signal will produce a fundamental frequency equal to the cylinder rate times the number of cylinders in the engine:

$$\text{EFR} = \text{CR} \times \text{No. of cylinders}$$

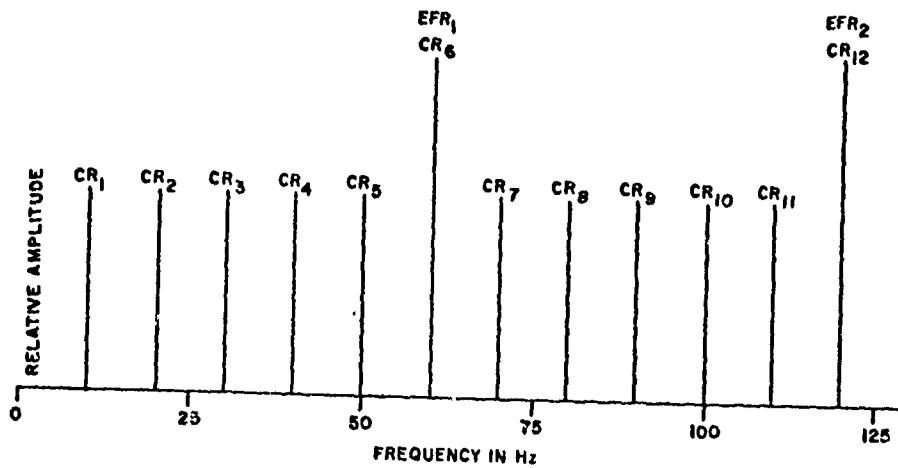
The example shown in figure 22 is assumed to have eight cylinders which results in an EFR of 40 Hz. Therefore, the EFR signal will be coincident with every eighth harmonic of the cylinder rate and every fourth harmonic of the crank shaft rate. As a result, this triple reinforcement will produce the strongest signals present in the spectral analysis of the four-cycle engine.

In summary, the sounds generated in a four-cycle diesel or gasoline engine are the crank shaft rate, cylinder rate and engine firing rate. The harmonics of the CSR reinforce the even harmonics of the CR and appear stronger than the odd harmonics of the CR. When both signals are strong enough to be displayed, they present a pattern of alternating dark and light signals. As with the two-cycle engine, the EFR reinforces the CR harmonics equal to the number of cylinders, and generally is the strongest signal in a four-cycle engine signature.

Figure 23 compares the sound spectrum of a two-cycle and a four-cycle engine, both of which have six cylinders operating at 600 RPM.



A. 4-CYCLE, 6-CYLINDER, 600 RPM DIESEL ENGINE



B. 2-CYCLE, 6-CYLINDER, 600 RPM DIESEL ENGINE

Figure 23. Sound Spectrum of 2-Cycle and 4-Cycle Engines

e. Auxiliary Lines

A signature will often contain discrete frequencies or harmonics series that are not associated with the target's engine system. Such signals are grouped in a broad term as auxiliary lines. The most common auxiliary line is the gear mesh rate line from ground vehicle transmissions and universals.

A sample signature of an auxiliary line is shown in figure 24.

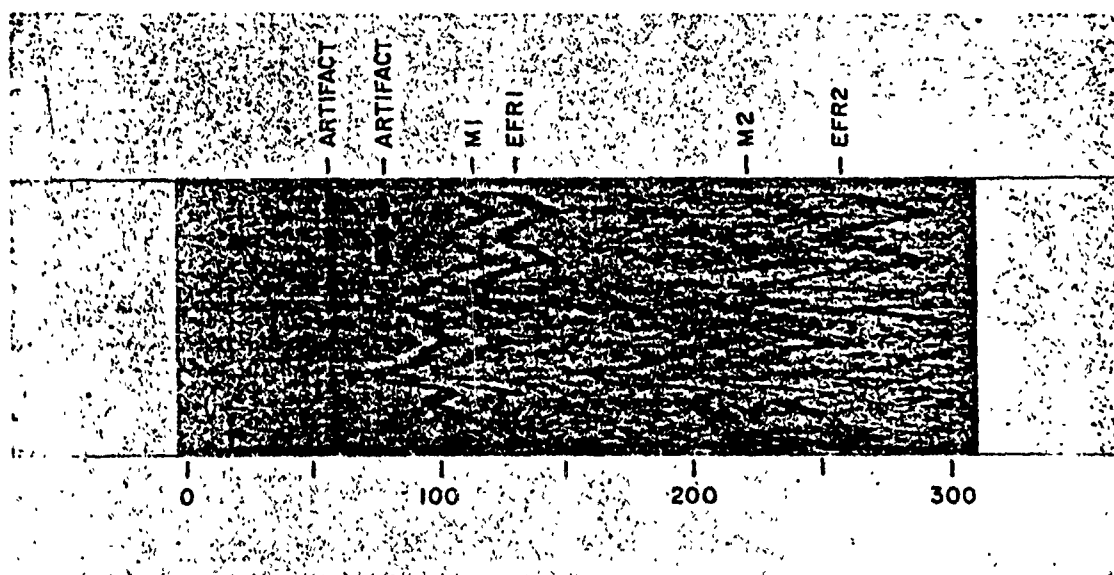


Figure 24. Signature of U.S. Jeep

This is a typical signature of a U.S. jeep travelling on a hard-packed dirt and gravel road:

U.S. Jeep  
four-cycle, four-cylinder  
EFR 63.4 Hz  
CR 15.8 Hz  
CSR 31.6 Hz  
Engine RPM 1896

Note generator mesh line falling at 104.3 Hz.

APPENDIX C

Excerpts from Vehicle Classification,  
NADC-SD-7191, Final Report No. 6, 6 Dec. 1971

#### 4. CLASSIFICATION ANALYSIS

The emphasis in this report is on the identification of vehicles by means of their radiated signatures. To this end, acoustic, magnetic, and seismic vehicle signatures were analyzed. In practice, of course, any sensor receiving sounds from vehicles must be expected to also receive sounds from the environment. An early step in the recognition task, therefore, must be to extract the vehicular sounds from other noises. Having performed this operation, two others must be performed on the signals to effect a recognition:

(1) A set of descriptors must be extracted from the signature which uniquely identifies the vehicle under observation, and

(2) The choice of an appropriate technique to utilize these descriptors most effectively must be made.

The basic program considered both the spectral and wide-band signal in the time and frequency domain with linear and non-linear processing. The models are as yet insufficiently defined to permit analytic generation of the complete and sufficient statistics which are necessary if a minimal set of coordinate discriminators in the N-dimensional discrimination space are to be determined. Needless to say, the fuzziness of the discriminators will limit any classification, manual or automatic, in terms of accuracy. Because of the very limited data base in terms of vehicle variety, these results will be preliminary in nature. When sufficient statistics are generated, the

result will provide a solid performance base.

The discrimination algorithms developed must stand the test of repeated application to signals not utilized in the algorithm development, i.e., they must remain statistically significant over a wide sample range. The phenomena to be avoided are those fortuitous relationships which statisticians point to, showing high correlation, but not relationship, and cannot stand the test of prediction into the future. Data crunching alone is not enough, one must have enough data not only to develop an algorithm, but also to test its reliability under varying conditions. The approach being taken to avoid these problems of accidental, hence unreliable, correlation, is to proceed from mechanical phenomena.

As a result of the initial reduction and analysis, it was decided to use primarily acoustic data for developing the classification manual. This was based on the fact that sufficient discriminants were contained in the acoustic signature to classify all targets of the data base. Additionally:

- (1) No useable data was present on the AC magnetic signature tapes.
- (2) The DC magnetic signatures contained the normal dipole response and little else. Although lines were present in some signatures, up to as high as 125 Hz, it was impossible to determine if they were true magnetic signatures, or, in fact, signatures due to seismic contamination in the input response.

(3) The seismic signatures appear to be similar to the acoustic, but generally lower in SNR. However, certain second order characteristics may provide useful additional discriminants as the data base is increased and automatic classification techniques are implemented. In addition to the negative aspects of the magnetic and seismic vehicle signal content, the following positive aspects are why acoustics provide the most promise for present and future detection and classification systems:

(4) The acoustic outputs of vehicles are rich in energy of a definable and extractable type, more explicitly, acoustic signatures provide the highest information content. It follows, therefore, that the higher the information content the larger is the discrimination base. This is very important because as the number of vehicles in the data base increases, the greater the requirement for more detailed discriminants for identification. Additionally, it lends itself to easily applicable direction finding and directional techniques, providing more basic information about the vehicle.

(5) Acoustic source energy is very high, providing the highest SNRs and therefore, the longest detection and classification ranges which are consistent and predictable on a world-wide basis. In cases in which the long range is a problem there exist techniques for making the propagation loss inverse cube or higher laws. These techniques should prove effective against aircraft interference at long ranges and low altitudes. The near overfly situation is also aided by these



techniques because the system has nulls both overhead and underneath in the microphone pattern to attenuate both the direct and ground reflected sound rays from the aircraft. These techniques can be switched in or out so that the same systems have both long range capability when needed and short range when desired - as for example, to count the elements of a convoy. In general, long range is desirable because fewer sensors are required to monitor a given area or road and simpler logistics are required for air emplacement since proximity to the target path is not mandatory.

(6) The acoustic signature is directly related to the configuration and physics of the vehicle. This means that the class of distinguishable vehicles can be easily enlarged.

(7) The acoustic signal is difficult to spoof and camouflage.

Although acoustics do, in fact, have the largest dynamic range of discriminants, it is recognized that if the data base is substantially increased, other means such as seismic may be required to supplement this classification system. However, at the present time, acoustic signatures were found to be sufficient to classify the entire data base using techniques directly related to the physical mechanics of the vehicle radiation.

#### 4.1 Signature Analysis

The acoustic signal is generated by the interaction of a number of different sources, but the most important ones (at least in terms of recognition) are produced as the result of exciting a resonant structure (or a number of coupled resonant structures) with a forcing function approximating a train of impulses. The received signal is therefore an approximation to a succession of impulse responses

of the system. An effective way of analyzing an impulse response in order to obtain information about the original system is to calculate the power spectrum, which would then show peaks corresponding to the natural resonances, which are themselves related to the mechanical structure. Different vehicles, having different structures, would therefore be expected to show different patterns of resonances, and these differences might be used as the basis for identification. The major reduction effort, therefore, has been to subject all the vehicle signals to a spectral analysis. The various analysis procedures have been discussed in Section 3.

#### 4.1.1 Origin of the Signature

The sound spectrum of an internal combustion engine consists of several discrete frequency components which are related to the crankshaft, cylinder firing, and engine firing. The detailed analysis of a signature consists primarily of establishing harmonic relationships between these discrete frequency components, and relating these discrete components to the physical phenomena that produced them. The acoustic energy radiated by vehicles of the types described here is generated primarily by the engine with secondary radiation due to the drive train, and accessories. The application of the results of this analysis proved highly successful in classifying all the vehicles in the available data base.

##### 4.1.1.1 Crankshaft Rate (CSR)

Sound frequencies are produced at the crankshaft rate because of the dynamic imbalance of the revolving crankshaft and attached piston and connecting rod assemblies. Inertial forces act

along with dynamic imbalance in producing engine vibrations. The vibrations are transferred through the bearings, through the engine mounts, and through the body of the vehicle to the atmosphere. The crankshaft rate can be calculated by dividing the engine RPM by 60 (seconds in a minute).

$$\text{CSR} = \frac{\text{RPM}}{60} \quad (\text{Hz})$$

#### 4.1.1.2 Cylinder Firing Rate (CFR)

Sound energy at the cylinder firing rate (CFR) results from the repetitive ignitions in one cylinder of the engine and the fundamental is simply the number of firings which occur in any one particular cylinder in one second. The sound is produced by gaseous combustion and impact forces. The pistons are driven by combustion of air and fuel mixtures which produce expanding gas that forces the pistons to turn the crankshaft. The impact forces can be thought of as the force of the piston impact against the cylinder walls.

In a four-cycle, or four-stroke engine, the CFR is equal to  $\frac{1}{2}$  the CSR, while in a two-stroke engine the CFR is the same as the CSR. In a two-cycle (stroke) engine an explosion occurs in each cylinder every time the crankshaft revolves. In a four-cycle engine the crankshaft revolves twice between each cylinder firing. For this reason, a two-cycle engine with the same number and size of cylinders as a four-cycle will have twice as many firings when running at the same RPM and consequently will have more power than a four-cycle engine. The following relation therefore holds:

$$\text{CFR} = \text{CSR} \text{ (2 cycle)}$$

$$\text{CFR} = \frac{1}{2} \text{ CSR (4 cycle)}$$

#### 4.1.1.3 Engine Firing Rate (EFR)

Engine firing rate is the total number of firings which occur in all cylinders of an engine in one second. Sound frequencies are generated at the engine firing rate due to repetitive firings in the engine cylinders. The sound is preceded by gaseous combustions, forces, and impact forces. Each time a firing occurs a vibration is set up. Cylinder firings are constantly occurring within a running engine and the sound frequency produced by all of them together will be at the rate of firings, in the engine. Therefore the engine firing rate equals the cylinder firing rate multiplied by the number of cylinders, or:

$$EFR = CFR \times \text{No. of Cylinders}$$

#### 4.1.1.4 Predominant Harmonic Pattern

The lowest frequency of interest to an analyst will be the cylinder firing rate. Harmonics of this fundamental will always be a part of the engine signature. Additionally, the frequency of the engine firing rate is related to the frequency of the cylinder firing rate by an integer multiplier (the number of cylinders). The engine firing rate frequency will therefore coincide with the frequency of one of the cylinder firing rate harmonics, and is usually the strongest line. Similarly, the frequency of the second harmonic of the engine firing rate will also coincide with the frequency of one of the cylinder firing rate harmonics. This coincidence of frequencies sometimes produces what is called a predominance pattern.

A predominant harmonic pattern is produced when some of the harmonics in a harmonic series appear stronger than the others in a

regular pattern. For example, a six cylinder engine might be expected to produce a pattern of six; every sixth harmonic of the cylinder firing rate is stronger than the preceding five harmonics due to the relationship between the cylinder firing rate and engine firing rate described above. In general, in-line six cylinder engines do produce a predominance pattern of six. However, the predominance pattern can be influenced by the design of the exhaust system. V-6 engines usually produce a pattern of three, which can be related to the "V" configuration of the engine and the mechanical design of the exhaust system. Patterns sometimes are not obvious at low order harmonics, but do become obvious in the mid to high frequency range.

#### 4.1.1.5 Drive Train and Accessory Lines

Another significant sound source for most vehicles is the drive train. The exact nature of the origin of drive train (DT) components is not known due to insufficient detailed information about the vehicles. However, the DT components that are present are extremely useful for classification purposes. In addition to engine and drive train lines, accessories such as pumps, generators, turbochargers, and auxillary motors can produce discrete frequency components. These accessory lines are not usually harmonically related to the other engine lines. The CFR lines and the DT lines each can usually be placed in a harmonic set. The frequency of each of the lines in a harmonic grouping is an integer multiple of the fundamental frequency. The spacing between adjacent lines in a harmonic grouping is therefore equal to the frequency of the fundamental of that grouping. The lines generated by accessories are usually weaker and higher in

frequency than the fundamentals of the other two. They are also mechanically coupled to the engine and therefore always track the CFR lines. When visible, they are very characteristic discriminants.

#### 4.1.1.6 Summary

A summary of the formulae for determining the CSR, CFR and EFR are given in Table 4.1.

<u>CSR</u>  CRANKSHAFT RATE	6 CYLINDER		8 CYLINDER		12 CYLINDER	
	2 CYCLE	4 CYLCE	2 CYCLE	4 CYCLE	2 CYCLE	4 CYCLE
	$\frac{\text{RPM}}{60}$	$\frac{\text{RPM}}{60}$	$\frac{\text{RPM}}{60}$	$\frac{\text{RPM}}{60}$	$\frac{\text{RPM}}{60}$	$\frac{\text{RPM}}{60}$
<u>CFR</u>  CYLINDER FIRING RATE	CSR	$\frac{\text{CSR}}{2}$	CSR	$\frac{\text{CSR}}{2}$	CSR	$\frac{\text{CSR}}{2}$
<u>EFR</u>  ENGINE FIRING RATE	CFR x 6	CFR x 6	CFR x 8	CFR x 8	CFR x 12	CFR x 12
<u>EFR</u>	$\frac{\text{RPM} \times 6}{60}$	$\frac{\text{RPM} \times 6}{60 \times 2}$	$\frac{\text{RPM} \times 8}{60}$	$\frac{\text{RPM} \times 8}{60 \times 2}$	$\frac{\text{RPM} \times 12}{60}$	$\frac{\text{RPM} \times 12}{60 \times 2}$
	$\frac{\text{RPM}}{10}$	$\frac{\text{RPM}}{20}$	$\frac{\text{RPM}}{7.5}$	$\frac{\text{RPM}}{15}$	$\frac{\text{RPM}}{5}$	$\frac{\text{RPM}}{10}$

TABLE 4.1  
ENGINE SPECTRA FORMULAE  
C-10

#### 4.2 Example of Sonogram Analysis

This section presents an example of the detailed analysis used to determine the descriptors used in the vehicle classification manual developed by NADC.

Figs. 3 through 13 are actual Lava-grams displaying the M551 vehicle signatures for different gears and at idle. The Lava-gram (sonogram) presentation provides the data to the operator in the most accessible format. The vehicle descriptors are easily extracted with the aid of multi-point dividers.

##### 4.2.1 Engine Idle Signature: Figs 3, 4 & 5

The engine signature exhibits a predominance pattern of three, but some of the intermediate lines are also strong. This is probably due to the mechanical design of the V6 engine and exhaust system. Very weak lines which are not harmonically related to the cylinder firing rate harmonics are visible between the 2nd and 3rd, 7th and 8th, 13th and 14th, and 14th and 15th CFR harmonics, but they are probably too weak to be of use operationally. The CFR spacing of 10.5 Hz at engine idle indicates that the 6V53T is a two-stroke engine. A 10.5 Hz CFR would result in 1260 RPM for a four-stroke engine and 630 RPM for a two-stroke engine.

$$\begin{aligned}
 \text{RPM} &= \frac{\text{EFR} \times 60}{\frac{1}{2} \times N_c} & \text{RPM} &= \frac{\text{EFR} \times 60}{N_c} \\
 &= \frac{6 \times 10.5 \times 60}{\frac{1}{2} \times 6} & &= \frac{6 \times 10.5 \times 60}{6} \\
 &= 1260 & &= 630
 \end{aligned}$$

Since the engine is governed to a maximum of 2800 RPM, it is unlikely that the engine would idle at 1260 RPM.

#### 4.2.2 4Th Gear Signature Figs. 6, 7 & 8

The signature in 4th gear consists of a strong engine firing rate (193 Hz), a strong drive train component (110 Hz), and a trace of CFR 3 and CFR 5. There is also an indication of many closely spaced lines below the CFR 3. The drive train component appears nearly the same strength (gram intensity is a function of strength) as the engine firing line.

The EFR of 193 Hz results in a cylinder firing rate of 32.2 Hz, which corresponds to an engine speed of 1930 RPM. The ratio of the drive train fundamental (DT 1) to the cylinder firing rate (CFR) is 3.4 (110/32.2). This placed DT 1 between CFR 3 and CFR 4 (0.4 of the distance between 3 and 4).

#### 4.2.3 3Rd Gear Signature: Figs 9, 10, & 11

The vehicle signature in 3rd gear is characterized by a strong engine firing rate (237 Hz), a strong CFR 5, and also by DT 1, DT 2 and DT 3. DT 1 is again nearly equal in strength to the EFR and appears mechanically related to the engine components (Standard Transmission). Traces of other cylinder firing rate harmonics are also visible. DT 2 and DT 3 are very close and appear to be a doublet. The EFR at 237 Hz results in a cylinder firing rate of 39.5 Hz which corresponds to an engine speed of 2370 RPM. DT 1 is at 60 Hz. The ratio of the drive train fundamental to the cylinder firing rate is 1.5 (60/39.5). The ratio of the gear ratio in 3rd gear to the gear ratio in 4th gear is 2.25 (3.24/1.44). The fact that the ratio of the



gear ratios is equal to the inverse of the ratio of the spacings of the two harmonic groupings tends to support the assumption that the harmonic grouping that is not related to the engine is associated with the drive train. The vehicle signature does not extend much above 350 Hz in third gear.

#### 4.2.4 2Nd Gear Signature: Figs 12 & 13

The vehicle signature in 2nd gear is characterized by two harmonic groupings. One grouping is associated with the engine, and exhibits a strong EFR (210 Hz) and CFR 5. The other grouping is associated with the drive train, and exhibits a strong fundamental (28.8 Hz) below CFR 1. There is an accessory line located between DT 3 and CFR 3. The ratio of the drive train fundamental to the cylinder firing rate is 0.82 (28.8/35). The ratio of this ratio in 3rd gear to this ratio in 2nd gear is 1.83 (1.5/0.82). The ratio of the gear ratio in 2nd gear to the gear ratio in 3rd gear is equal to 1.86 (6.04/3.24). This close agreement further supports the assumption that the harmonic grouping which is not harmonically related to the engine is associated with the drive train. The signature in 2nd gear extends up to 450 Hz.

NOTE: The 500 Hz and 100 Hz grams that have been presented have 2000 point frequency resolution, and the 250 Hz grams have 1000 point frequency resolution. This results in a frequency resolution of -.25 Hz on the 500 Hz frequency range, and 0.25 Hz on the 250 Hz frequency range. The time scale is stretched out by a factor of 2 on the 250 Hz frequency range. Two grams of this

signature with 500 point frequency resolution have been included for comparison purposes. Increasing frequency resolution is desirable because it improves the ability to resolve two lines that are close together since it enhances the ability to extract discrete components from background noise. However, there is a disadvantage to increasing frequency resolution which places a practical limit on the maximum frequency resolution that can be used. This disadvantage is associated with the fact that as frequency resolution increases, the response time of the spectrum analyzer to changes in amplitude or frequency also increases. The normal frequency variations associated with the discrete components of vehicle signatures limits the maximum resolution that can be used.

#### 4.3 Summary of Signature Characteristics

This section presents a general summary of vehicle descriptors determined from the analyses.

##### 4.3.1 U.S. M-35: 2½ Ton Truck

1. CFR-6 is strongest line in signature
2. Predominance pattern of six
3. Strong accessory line between CFR 16 and 17
4. Another accessory line between CFR 13 and CFR 14
5. No detectable drive train components
6. Four-stroke, in-line six cylinder engine
7. Fourth gear, additional accessory lines occur between CFR 11 and 12

4.3.2 Soviet ZIL-157 Truck

1. Strongest line CFR-6
2. CFR 12 and 15 also dominant
3. Drive train fundamental appears chopped on the gram.

(Changes in gram intensity apparent on DT 1)

4. Standard transmission, drive train mechanically coupled to the engine
5. Traces of accessory lines between CFR 2 and 3; CFR . and 8; CFR 9 and 10
6. Four-stroke, 6 cylinder in line engine, gasoline

4.3.3 Soviet PT-76: Amphibious Truck

1. Strong pattern of three
2. CFR-6 is strongest line
3. CFR 9 and 12 are also dominant
4. Drive train fundamental mechanically coupled to engine; standard transmission
5. At least 20 CFR harmonics are clearly visible
6. Drive train fundamental located between CFR 2 and 3
7. Drive train harmonic between CFR 7 and 8
8. Four-stroke, six cylinder engine

4.3.4 Soviet BTR-50: Armored Personnel Carrier

1. CFR 6 is strongest line
2. CFR 4 and 8 are also dominant
3. No discernable pattern except at high order
4. At least 20 CFR harmonics are clearly visible

5. Drive train fundamental mechanically coupled to engine;  
standard transmission

6. Drive train harmonic between CFR 7 and 8

7. Four-stroke, six cylinder engine

4.3.5 U.S. M113A1 Armored Personnel Carrier

1. Strongest line in signature is CFR 3

2. CFR 9 is also dominant

3. Drive train not mechanically coupled, automatic  
transmission

4. CFR 6 greater than 135 Hz

5. Two-stroke - six cylinder engine

4.3.6 U.S. M-551 Armored Reconnaissance/Airborne Assault Vehicle

1. CFR 6 is strongest line in signature

2. CFR 5 is also strong

3. Strong drive train fundamental mechanically coupled to the  
engine, standard transmission, although data sheets indicate the  
vehicle used fluid drive

4. The drive train line is as strong as CFR 6

5. CFR 6 is greater than 135 Hz

6. Two-stroke V-6 engine

4.3.7 U.S. M-60 Combat Tank

1. Strong predominance pattern of three

2. Strong CFR 6 and CFR 3

3. Strong drive train in high gear

4. Two transmission modes

(a) automatic in high gear

(b) standard transmission in low gear

5. Accessory line coincide with CFR 3 and 6 on the grams

6. Four-stroke, V-12 engine

4.3.8 Soviet T-55:Medium Tank

1. Strongest line in signature is CFR 12

2. Strong pattern of 3

3. Standard transmission, drive train mechanically coupled to engine

4.. CFR 15 also dominant

5. Four-stroke, 12 cylinder engine

4.4 Mechanical Characteristics

Table 4.2 and 4.3 list the mechanical characteristics of the Foreign and American vehicles used in the classification data base.

4.5 Classification Manual

Detailed analysis and classification procedures are described in NADC-SD-7179, "Vehicle Classification Manual". A summary is presented below:

The first step in the classification procedure is to select the strongest line on the gram and determine the group of lines to which it is harmonically related. Lining up the maximum number of lines, including the strongest line and zero frequency, establishes this group as the CFR harmonic set. The higher order (frequency) lines are associated with the CFR harmonic set and are very helpful in establishing the harmonic spacing and therefore the fundamental frequency.

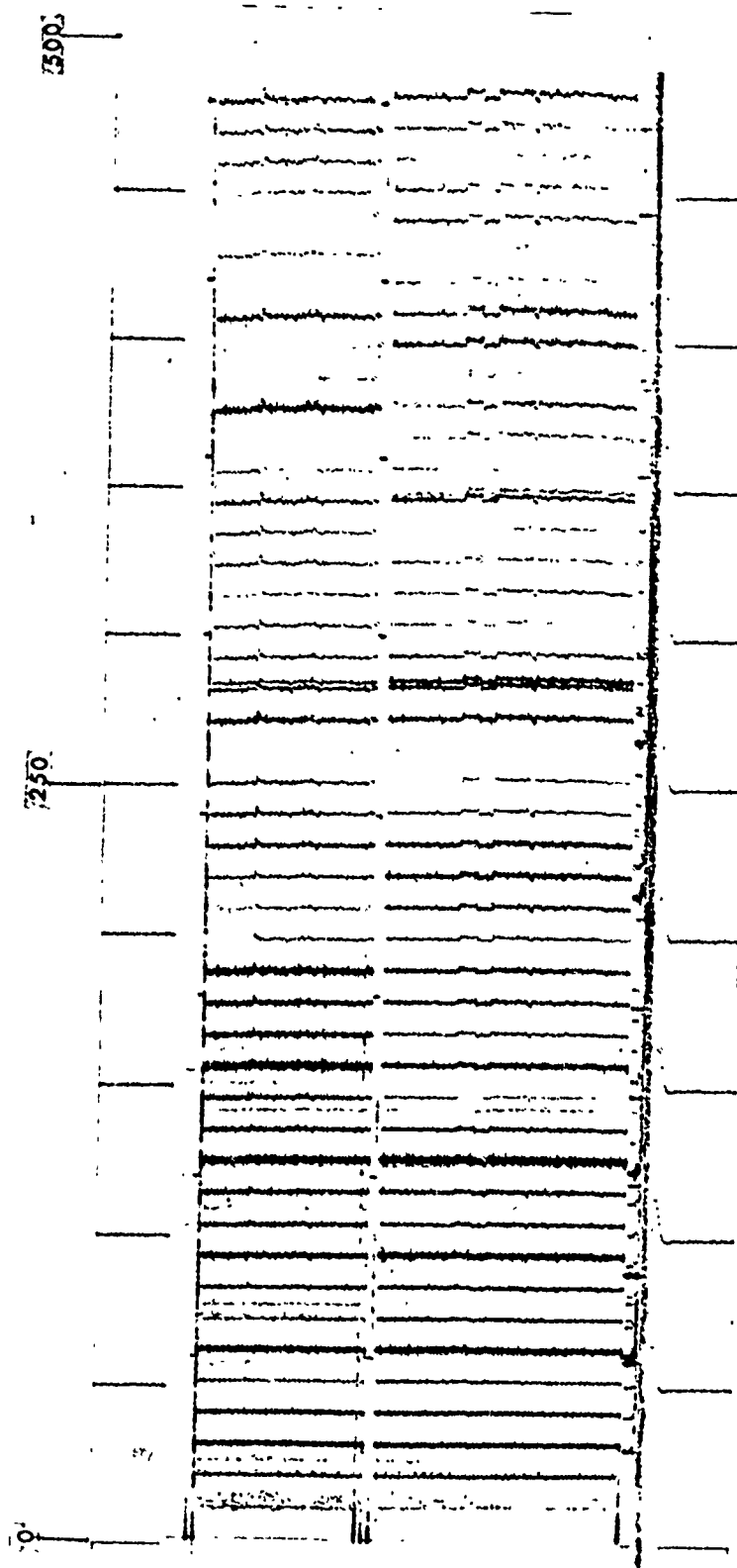


FIGURE 3 - ENGINE IDLE TEST  
M -551 U. S. TANK

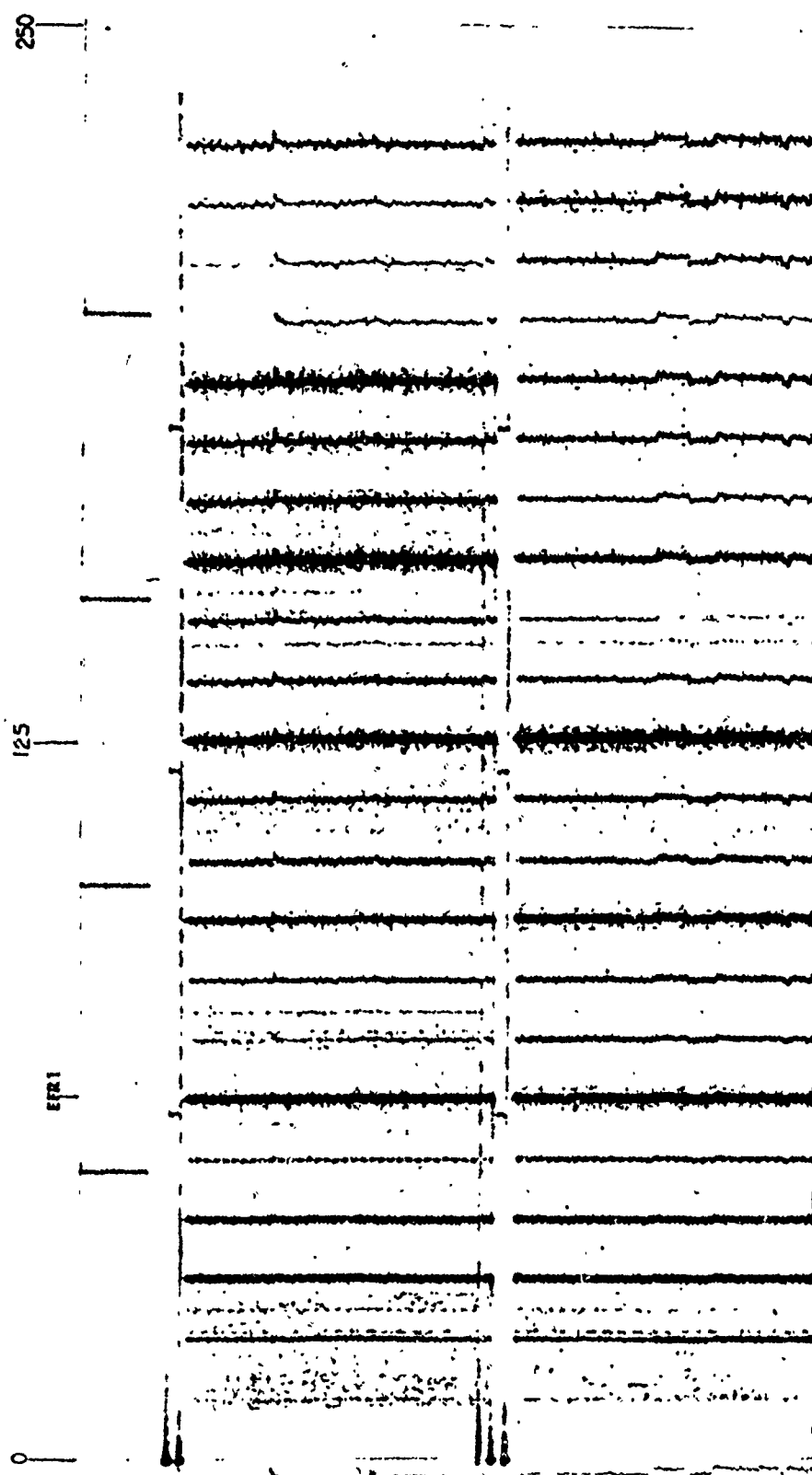


FIGURE 4 - ENGINE IDLE TEST  
M - 551 U. S. TANK

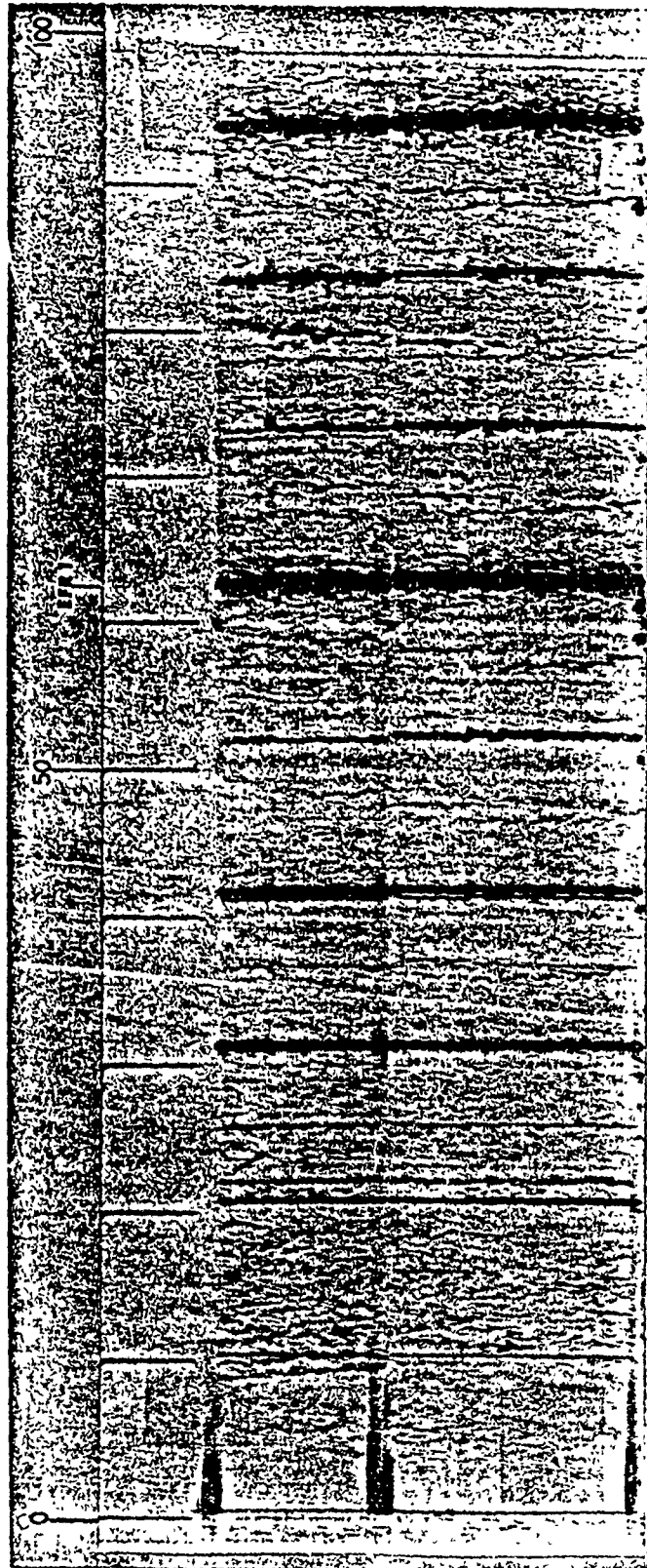


FIGURE 5 - ENGINE IDLE TEST  
M - 551 U. S. TANK



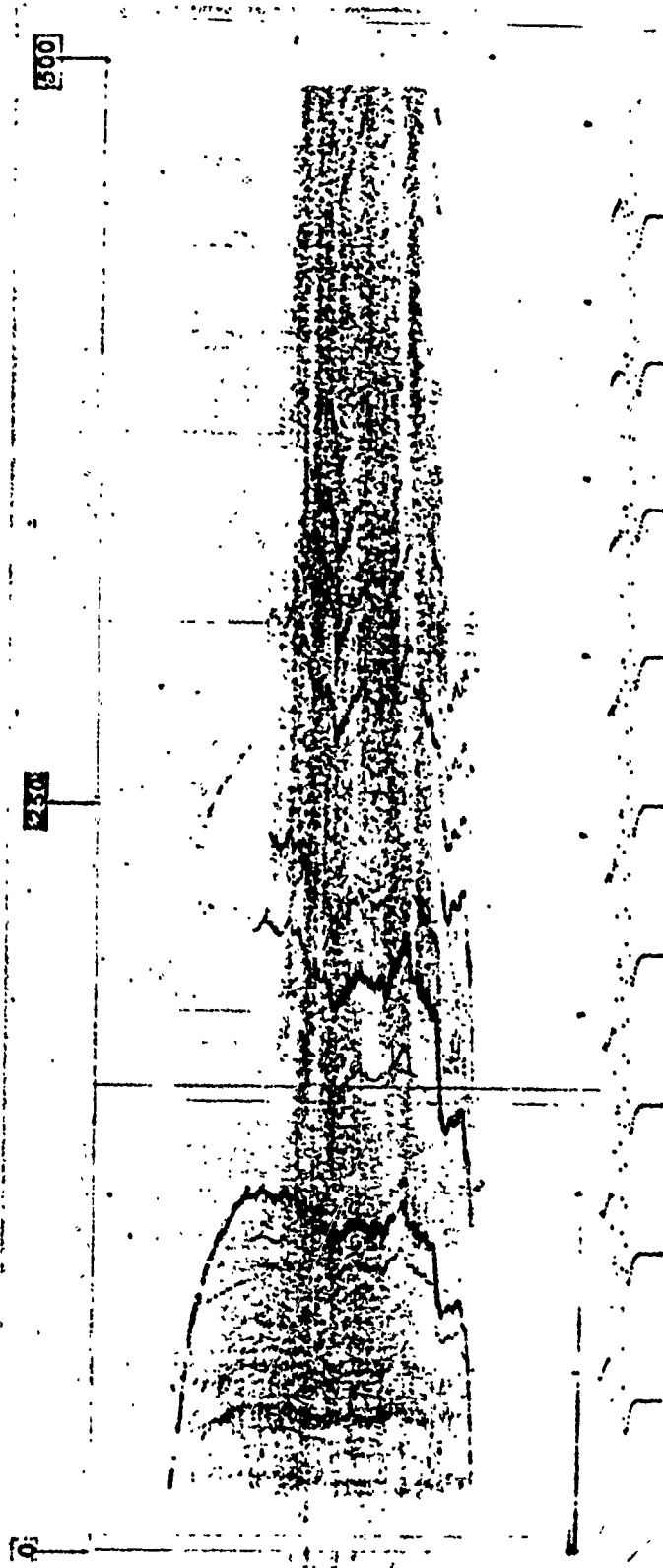


FIGURE 6 - VEHICLE SIGNATURE 4TH GEAR  
M- 551 U. S. TANK

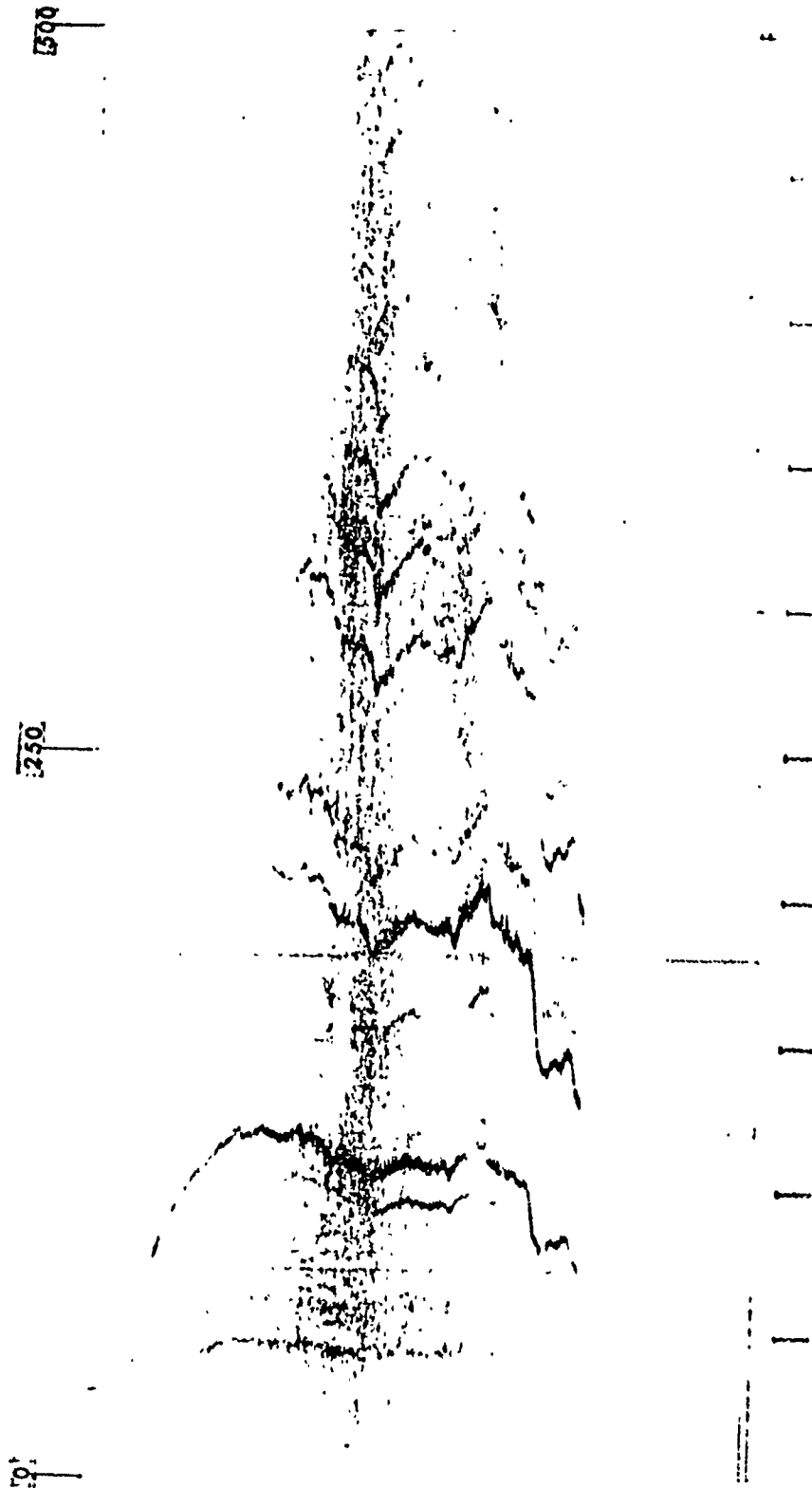


FIGURE 7 - VEHICLE SIGNATURE 4th GEAR, 500 POINT RESOLUTION

M-551 U. S. TANK

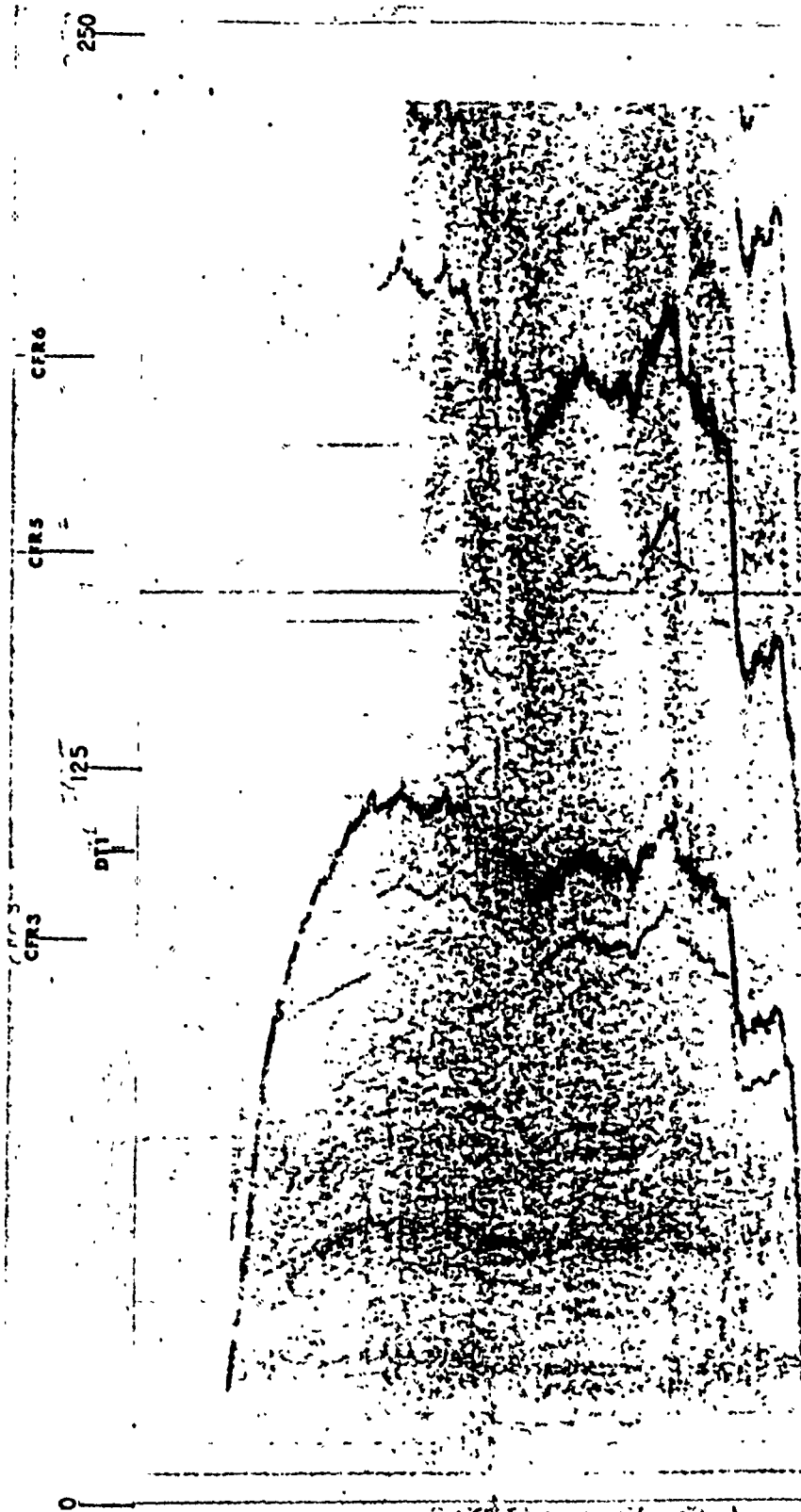


FIGURE 8 - VEHICLE SIGNATURE 4TH GEAR

M - 551 U. S. TANK

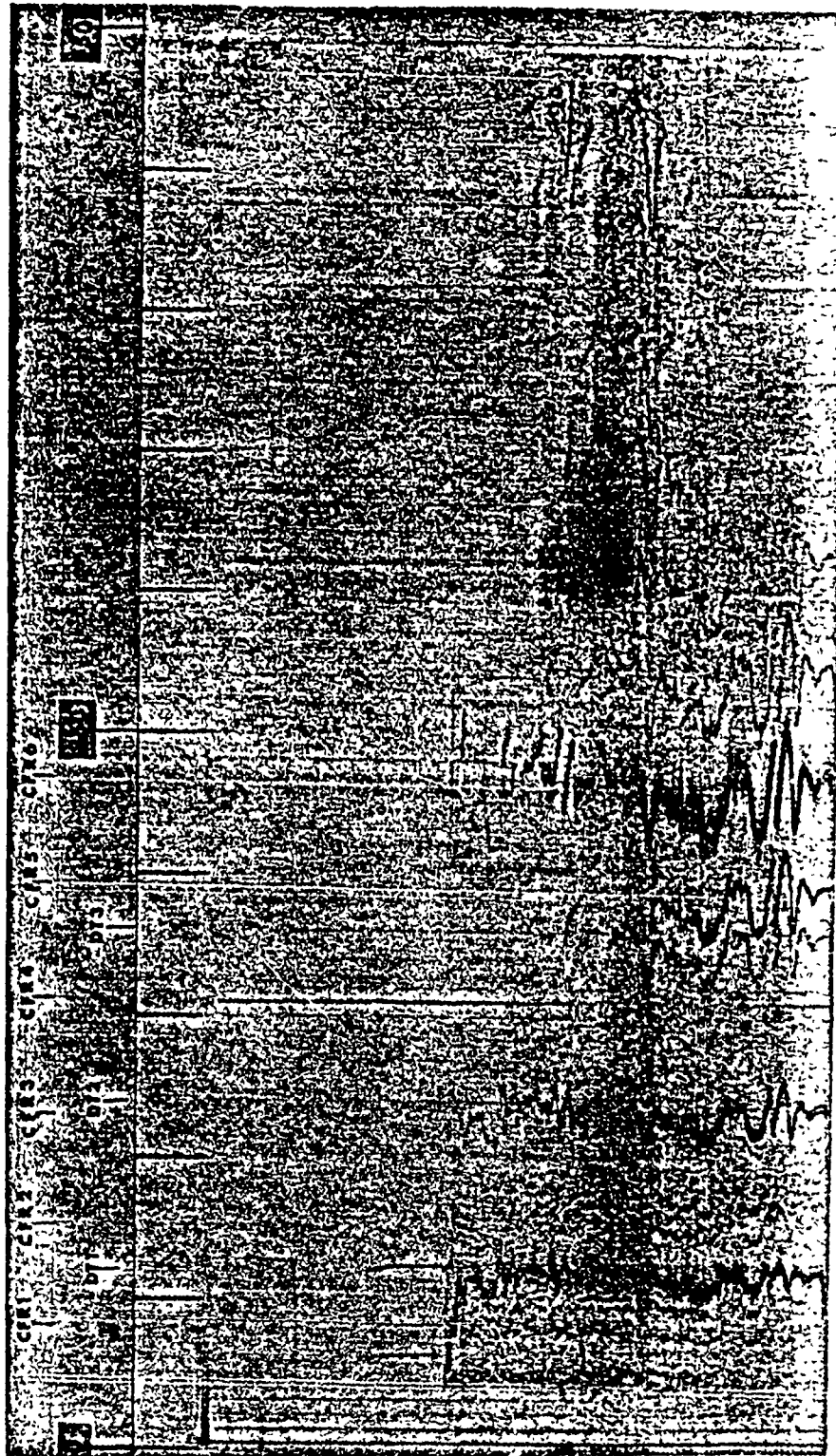


FIGURE 9 - VEHICLE SIGNATURE 3RD GEAR  
M-551 U. S. TANK

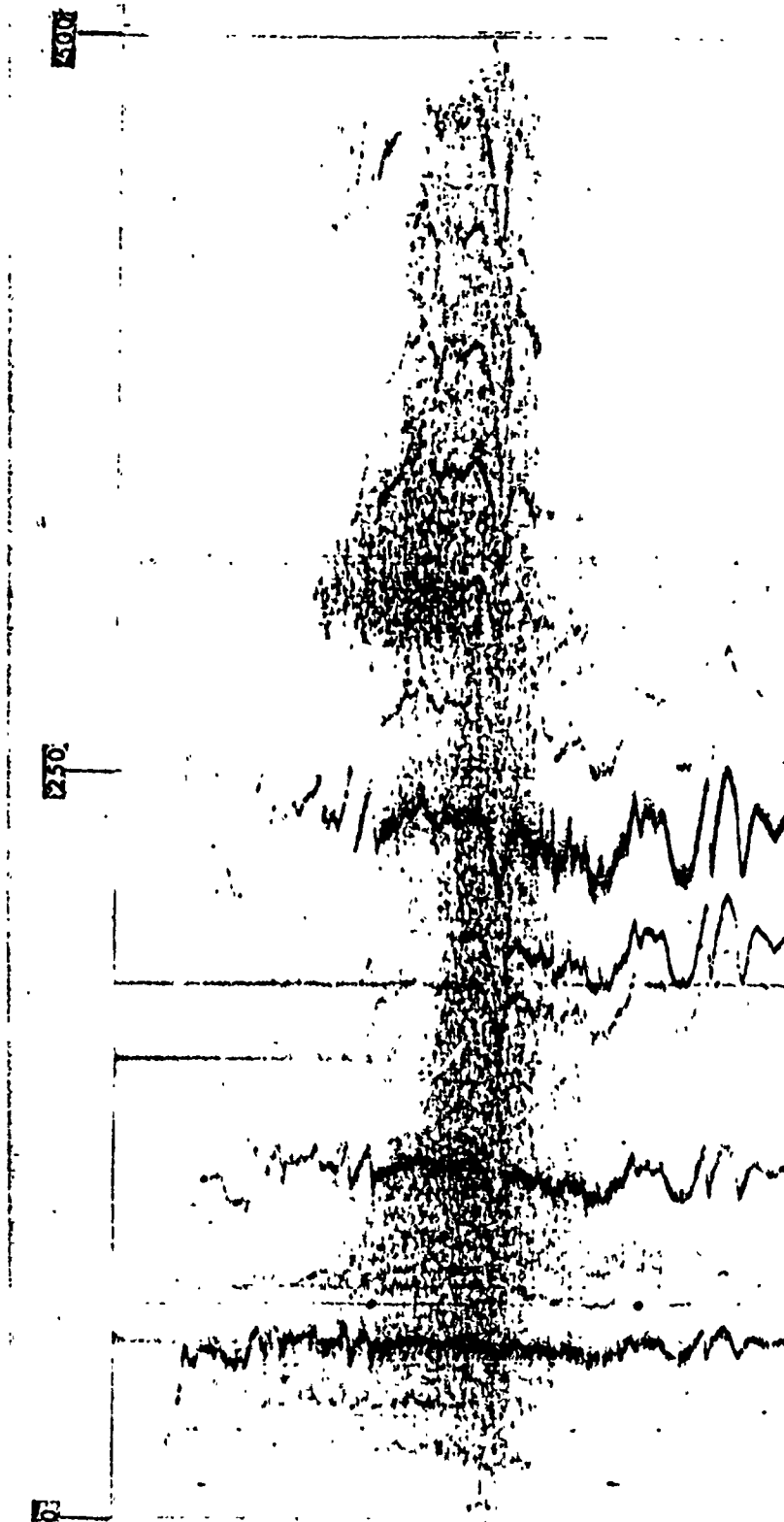


FIGURE 10 - VEHICLE SIGNATURE 3RD GEAR, 500 POINT RESOLUTION  
M-551 U. S. TANK

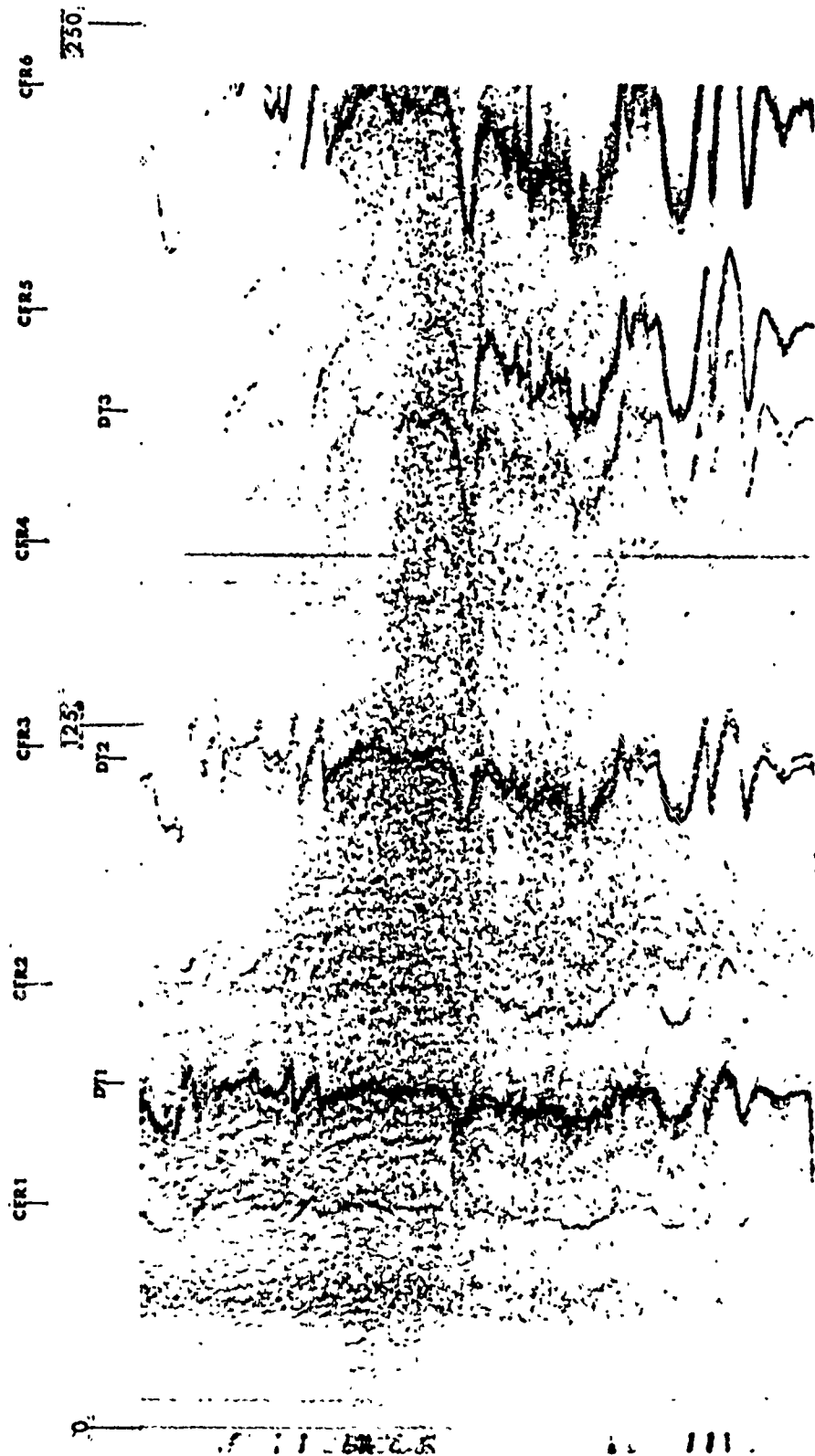


FIGURE 11 - VEHICLE SIGNATURE 3RD GEAR  
 M - 551 U. S. TANK

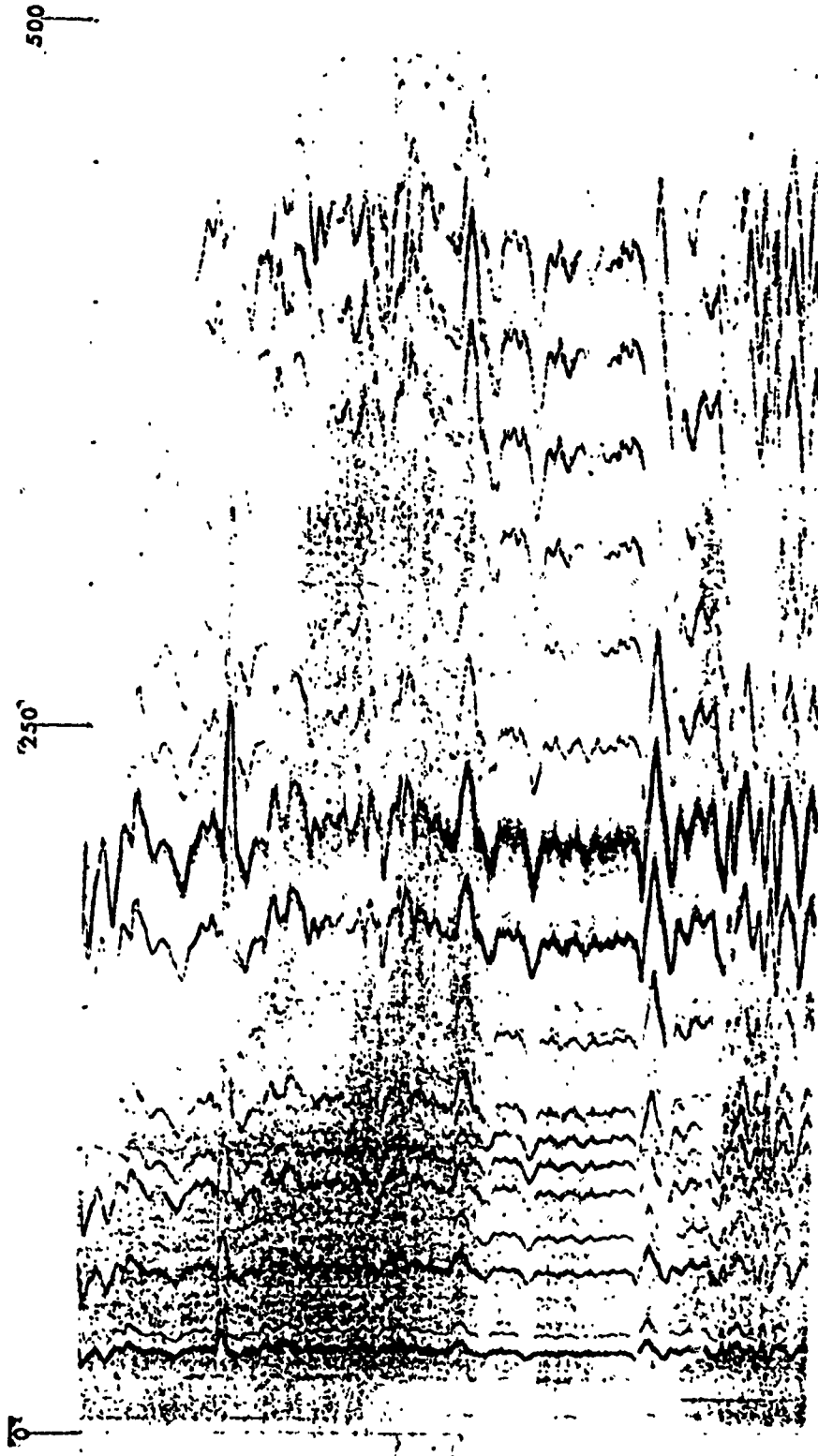


FIGURE 12 - VEHICLE SIGNATURE 2ND GEAR  
M - 551 U. S. TANK

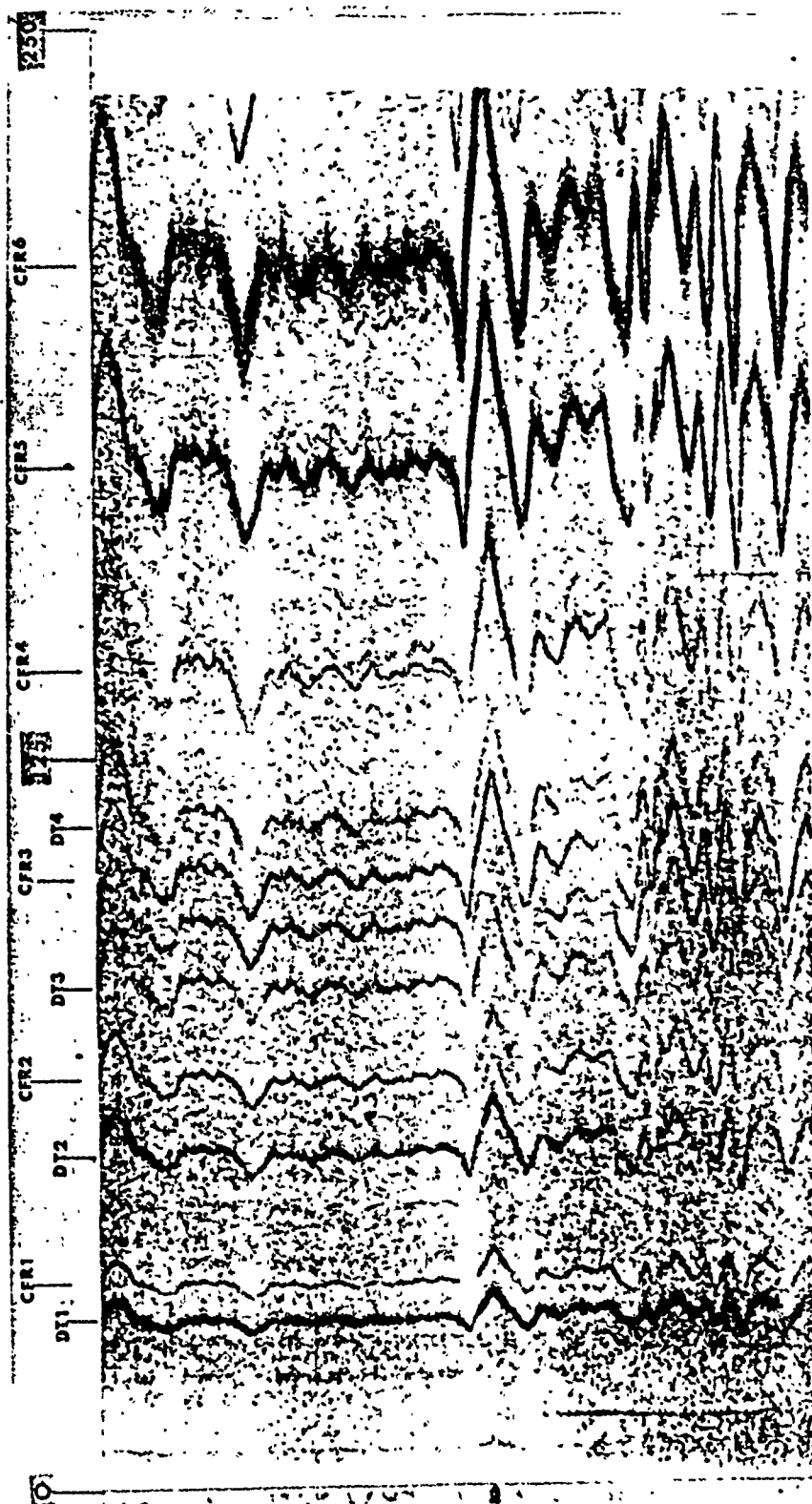


FIGURE 13 - VEHICLE SIGNATURE  
M- 551 U. S. TANK 2ND GEAR



VEHICLE	TRUCK, CARGO 2 1/2 T 6X6	CARRIER, PERSONNEL FULL TRACK	TANK, AMPHIBIOUS FULL TRACK	TANK, MEDIUM FULL TRACK
MODEL	ZIL 157	BTR 50 PKU	PT 76	T 55
COMBAT WT (LBS)	12,000	32,000	31,000	79,000
MAX SPEED IN GEAR 5	41	27	27	--
ENGINE TYPE	IN LINE 6	IN LINE 6	IN LINE 6	"V" 12
CYCLE	4	4	4	4
FUEL	GASOLINE	DIESEL	DIESEL	DIESEL
GROSS H.P.	109	240 @ 1800RPM	240 @ 1800RPM	570
GOVERNED RPM	--	--	2100	--
TRANSMISSION TYPE	MECHANICAL	MECHANICAL	MECHANICAL	MECHANICAL
GEAR RATIO				
1ST	6.24:1	5.57:1	5.57:1	6.00:1
2ND	3.32:1	2.60	2.60:1	2.80:1
3RD	1.90:1	1.86	1.86:1	2.00:1
4TH	1.00:1	1.22	1.22:1	1.43:1
5TH	0.80:1	0.76	0.76:1	0.91:1
R	--	--	4.95:1	0.91:1
FINAL DRIVE TYPE	--	--	--	CROSS DRIVE
RATIO	--	--	5.56:1	6.69:1
NO. OF SPROCKET TEETH	--	--	--	13
TRANSFER RATIO	2.44:1 & 1.44:1	--	--	0.70:1
AXLE RATIO	6.67:1	--	--	--
SUSPENSION TYPE	--	TORSION BAR	TORSION BAR	TORSION BAR
TRACK DATA PITCH (IN.)	--	5.0	5.0	5.5
WIDTH (IN.)	--	13.8	13.8	--
NO. OF ROAD WHEELS	6	12	12	10 DUAL
GROUND CONTACT PRESSURE (PSI)	--	7.26	--	11.51
MOBILITY INDEX	--	52.3	47.6	72.0
CONE INDEX	--	49.0	47.0	58.0

# VEHICLE CHARACTERISTIC DATA

VEHICLE	TANK, COMBAT, FULL - TRACKED, 105 MM	CARRIER, PERSONNEL, FULL - TRACKED, ARMORED	ARMORED RECONNAISSANCE AIRBORNE ASSAULT VEHICLE	TRUCK, CARGO 2 1/2 TON, 6-6
MODEL	M60A1	M48A1	M551	M35A2
COMBAT WEIGHT - LBS	105,000	23,400	33,500	23,400
MAX SPEED (MPH) IN				
1st GEAR	8	10	7	9
2nd "	30	20	10	16
3rd "	-	42.5	19	27
4th "	-	-	43	44
5th "	-	-	-	56
R.	8	9	5	5
R.	-	-	9	9
ENGINE				
MODEL	AVIDS-1790-2	6V-53	6V-53T	LD-465-IC
TYPE	12 CYL - 4CYC-AIR COOLED	6 CYL - 2CYC-LIQUID COOLED	6 CYL - 2CYC-LIQUID COOLED	6 CYL - 3CYC-LIQUID COOLED
DISPLACEMENT - CU IN	1791	318	318	478
BORE - IN	5.75	3.875	3.875	4.562
STROKE - IN	5.75	4.5	4.5	4.875
GOVERNED SPEED-RPM	2400	2800	2800	2600
COMPRESSION RATIO	16:1	21:1	17.5:1	22:1
FUEL	DIESEL, VV-F-800	DIESEL, VV-F-800	DIESEL, VV-F-800	DIESEL, VV-F-800
GROSS HORSEPOWER	750	202	300	140
GROSS TORQUE	1710 LB FT @ 1800 RPM	425 LB FT @ 1500 RPM	615 LB FT @ 2100 RPM	340 LB FT @ 1600 RPM
FIRING SEQUENCE	1-2-4-3-5-6-7-8-9-10-11-12	1-2-4-3-5-6-7-8-9-10-11-12	1-2-4-3-5-6-7-8-9-10-11-12	1-2-4-3-5-6-7-8-9-10-11-12
WEIGHT - LBS	4527	1300	1100	1500
FAN RATIO	2:1	1348:1	1.5:1	1.35:1
EXHAUST SYSTEM DESCRIPTION	4 MANIFOLDS, 2 1/2 IN DIA. STAINLESS APPROX 4 FT LONG 2 STAINLESS OUTLET TUBES 4 1/2 DIA, 2 FT LONG, 2 TURBO CHARGERS - SNITZER D-65	EXHAUST PIPE WITH MUFFLER, APPROX 4 FT LONG, 25 LBS.	Y PIPE WITH MUFFLER, EXHAUST PIPE, APPROX. 5 FT LONG, 40 LBS. 1 TURBO CHARGER	CAST-THREE PIECE MANIFOLD 3 IN. STAINLESS EXHAUST, 2 1/2 FT LONG. 5 BY 2 1/2 IN. MUFFLER. 3 IN. STAINLESS TAILPIPE 8 FT LONG.
TRANSMISSION				
TYPE	CROSS-DRIVE	3 SPEED AUTOMATIC	CROSS-DRIVE	MECHANICAL
MODEL	CD850-6A	TX-100	XTC-250	10B72194
TORQUE CONVERTER	SINGLE STAGE - MULTI PHASE	SINGLE STAGE - MULTI PHASE	SINGLE STAGE - MULTI PHASE	-
MULTIPLICATION	3.6 : 1	3.5 : 1	2.55 : 1	-
GEAR RATIOS				
1st	2.99 : 1 (LOW)	3.81 : 1	6.16 : 1	5.02 : 1
2nd	1.08 : 1 (HIGH)	1.93 : 1	4.18 : 1	2.78 : 1
3rd	-	1.00 : 1	2.24 : 1	1.62 : 1
4th	-	-	1.00 : 1	1.00 : 1
5th	-	-	-	0.79 : 1
R.	4.23 : 1	4.35 : 1	8.76 : 1	4.90 : 1
R.	-	-	4.69 : 1	-
WEIGHT - LBS	3000	309	1300	300
FINAL DRIVE				
TYPE	SPUR GEAR	GEARED TYPE	INTEGRAL WITH TRANSMISSION	-
RATIO	5.08 : 1	3.93 : 1	2.22 : 1	-
TOTAL OVERALL USABLE RATIO	35.2	50.5	25.2	67.3
SPROCKET				
PITCH DIA.	24.5	19.6	16.7	-
NO OF TEETH	11	10	11	-
TRANSFER RATIO	-	1:1286	-	130:1 - 100:1
AXLE RATIO	-	-	-	6.72:1
SUSPENSION TYPE	TORSION BAR	TORSION BAR	TORSION BAR	LEAF SPRINGS
TRACK DATA				
PITCH IN.	9.64	6.6	4.7	-
WIDTH IN.	28	15	17.5	-
NO OF SHOES	80-80	63L-64R	102-102	-
LENGTH IN.	780.64	376-374	472.4	-
ROAD WHEELS				
NUMBER - SIZE	24-26 BY 1/2 IN.	10-24 BY 2 1/2 IN	10-28 IN	10-500+20
MATERIAL	STEEL WITH RUBBER	ALUMINUM WITH RUBBER	ALUMINUM WITH RUBBER	STEEL WITH-TIRE
OFFSET OF WHEELS-IN	3 3/8	2 1/4	4 3/8	-
TIRE DATA				
DIAMETER IN.	-	-	-	41.1
WIDTH IN.	-	-	-	9.0
DISTANCE TRAVELED/REV FT	-	-	-	10.02
GROUND CONTACT PRES PSI	113	76	6.86	-
MOBILITY INDEX	75	50	41.4	57
COKE INDEX	59	43	44	61
ELECTRICAL SYSTEM				
VOLTAGE	24	24	24	24
GENERATOR AMPS	300	100	300	25
BATTERY TYPE - HQ	6TN, 12V - 6	6TN, 12V - 2	6TN, 12V - 2 OR 4	6TN, 12V - 2
AUXILIARY MOTORS	6TN, 12V - 6 ELECTRIC STARTER, PERSONNEL WATER PUMP, VEILATING BLOWER, AIR LINE BLENDER MOTOR, 115 POWER TRANSFORMER & ELECTRIC DIMMER MOTOR, COMPASS FLARE MOTOR.	6TN, 12V - 2 ELECTRIC STARTER, PERSONNEL WATER PUMP, VEILATING BLOWER, AIR LINE BLENDER MOTOR, 115 POWER TRANSFORMER & ELECTRIC DIMMER MOTOR.	6TN, 12V - 2 OR 4 ELECTRIC STARTER, PERSONNEL WATER PUMP, VEILATING BLOWER, AIR LINE BLENDER MOTOR, 115 POWER TRANSFORMER & ELECTRIC DIMMER MOTOR, COMPASS FLARE MOTOR, SUPPLY VENTILATOR AND BLEND GAS AND COMPRESSION MOTOR.	6TN, 12V - 2 ELECTRIC STARTER, PERSONNEL WATER PUMP, VEILATING BLOWER.

If any additional lines can be placed into another harmonic set with, at least, its fundamental below 100 Hz it probably will belong to the drive train set. At this time, it should be established whether these two sets are mechanically related. If they are, the transmission is manual, if not, then the transmission is automatic. Lines not included in either set are probably those due to accessories. These lines are mechanically coupled to the crankshaft and will therefore be in phase with the cylinder firing lines. Accessory lines provide unique and therefore valuable information on particular vehicles. Sometimes lines appear to be broken or chopped. This phenomenon is due to a lack of frequency resolution resulting in the analyzer's inability to separate two very closely spaced lines (doublet). Sometimes a DT line and a CFR line combine to form this single chopped line. For example in the case of the ZIL-157, the first two DT lines are doublets and are chopped. These doublets are both apparently generated by drive train components which are rotating at about the same frequency. With these few operations, sufficient information is obtained to answer a specific list of questions. Table 4.4 is the list of questions which have been designed to extract the pertinent vehicle descriptors from a sonogram. When answered, the vehicles of the data base can uniquely be identified. After answering these questions two classification techniques are available to the analyst:

- (1) Decision Tree Technique (Table 4.5)
- (2) Matrix Technique (Table 4.6)

TABLE 4-4  
ANALYSIS QUESTIONNAIRE

1. Select the strongest CFR on the chart and determine its harmonic order.

(3, 6, 9, 12, 15)

2. What is the frequency of CFR 6? ( Hz )

3. What is the frequency of CFR 1? ( Hz )

4. List the next three dominant lines by harmonic order. Listed by relative signal strength? ( \_\_\_\_\_, \_\_\_\_\_, \_\_\_\_\_ )  
2nd 3rd 4th

5. Is there an accessory line between CFR 16 and CFR 17? (Yes, No.)

6. What is predominant pattern of the CFR set? (3, 6, 12, none of these)  
(A pattern must include the strongest line and be repeated at least twice consecutively.)

7. Undiminished CFR. Are there at least 20 consecutive CFR lines visible on the gram of gradually diminishing strength? (Yes, No)

8. Are there DT 1 lines between the following CFR lines: (Yes, No)  
(Dt 1 may not be visible and must be determined with dividers) 0 & 1  
1 & 2  
2 & 3  
3 & 4  
7 & 8  
— & —

9. What is the frequency of the DT fundamental? ( Hz )

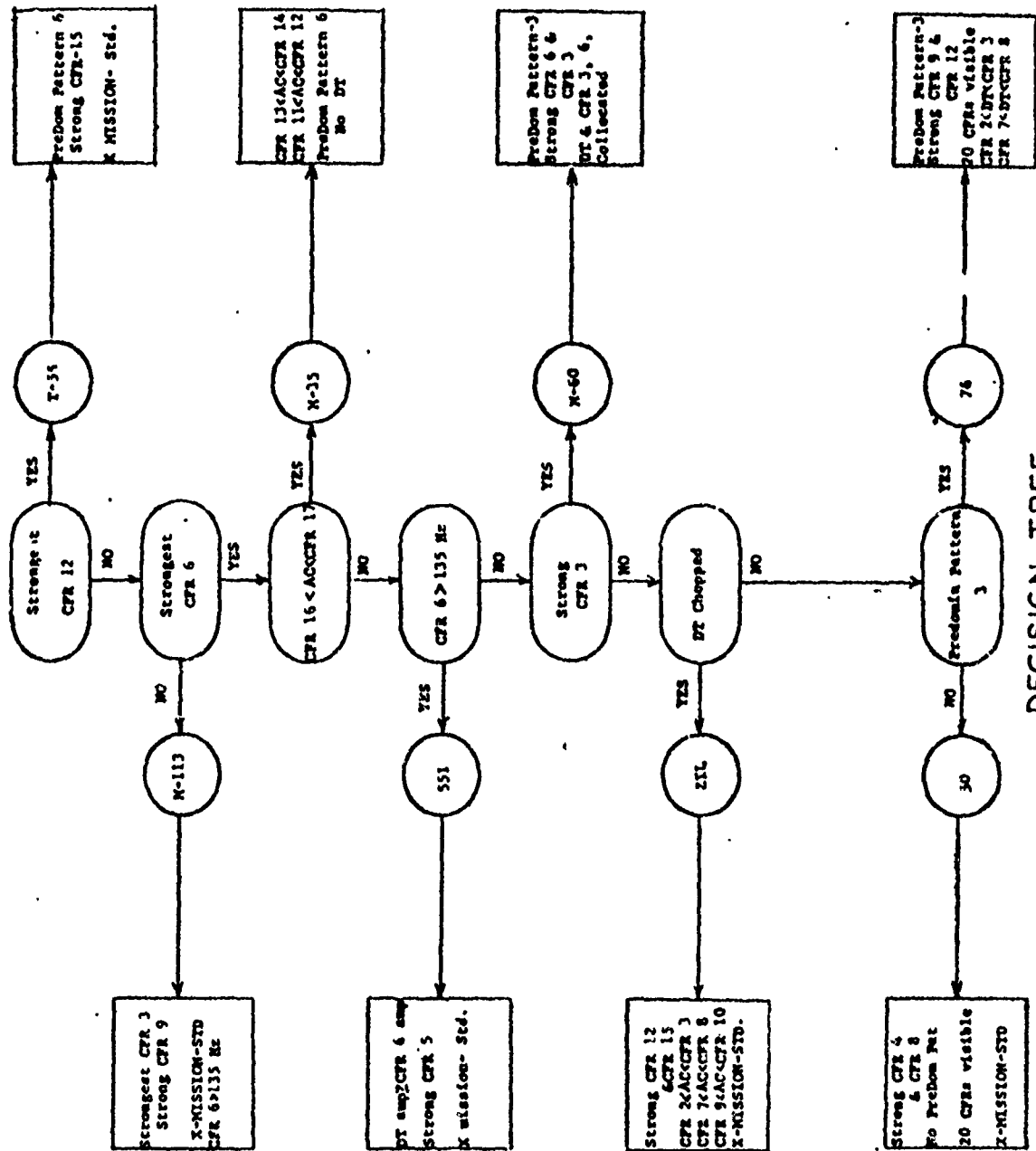
10. What is the relative strength of DT as compared to CFR 6?  
(weak, strong, very strong)

11. Are there any chopped DT lines below 100 Hz? (Yes, No)

12. Is the DT mechanically coupled to the engine i.e., are the DT lines in phase with the CFR lines?  
(Yes - Manual transmission)  
(No - Automatic transmission)

13. What is the ratio of the frequency of DT divided by CFR fundamentals?  
( \_\_\_\_\_ )

14. Are there any accessory lines between the following CFR lines?  
2 & 3  
5 & 6  
11 & 12  
13 & 14  
— & —



DECISION TREE  
TABLE 4-5

# VEHICLE CLASSIFICATION MATRIX

DISCRIMINANTS	VEHICLE		M 35					ZIL 157					M 113					M 551					BTR 50					PT 76					M 60					T 55				
	GEAR		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5					
STRONGEST CFR						6	6					6	6									6	6																			
OTHER STRONG CFR	A					12	12					12	12																													
	B					-	-					15	15																													
TRANSMISSION TYPE						M	M					M	M																													
STRONG DT	(1)					-	-					X	X																													
PREDOMINANCE PATTERN						6	6																																			
ALL CFR'S TO CFR 20						-	-																																			
CFR 16 < AC < CFR 17	(2)					X	X																																			
CFR 13 < AC < CFR 14						X	X																																			
CFR 11 < AC < CFR 12						-	X																																			
CFR 7 < DT < CFR 8						-	-																																			
AC JUST BELOW CFR 6						-	-																																			
CFR 2 < AC < CFR 3						-	-																																			
DT < CFR 1						-	-																																			
CFR 1 < DT < CFR 2						-	-																																			
CFR 2 < DT < CFR 3						-	-																																			
CFR 3 < DT < CFR 4						-	-																																			
CFR 4 < DT < CFR 5						-	-																																			
AMPLITUDE DT ≥ CFR 6						-	-																																			
CFR 6 > 135 Hz.						-	-																																			
DT CHOPPED AND NOT CFR COINCIDENT						-	-																																			
RATIO DT 1 CFR 1	(3)					(4)	(4)					4.31.8						1.81.0																								

☐ = Discriminant absent

☒ = Discriminant present

③ Variable for automatic transmission

④ No DT visible

① DT = DRIVE TRAIN LINE(S)

② AC = ACCESSORY LINE

7A 'E. 4-6

The Decision Tree, Table 4.5, although not providing as high a confidence level as the Matrix, is quicker. It leads to a direct, single answer. The Decision Tree is a short cut method and does not require using all available data. The main trunk of the tree contains basic data for all vehicles. As the operator proceeds, he is directed down one set of branches. The further he moves, the more specific are the questions until only a single vehicle is left on the remaining branch. If vehicles are similar, or signatures weak, erroneous paths can be taken and wrong decisions made. The Matrix, Table 4.6, on the other hand, uses all available information and is therefore more reliable. Additionally, it may serve as a good check on questionable decision tree classifications.

Both techniques require simple yes/no type decisions to be made or parameters to be circled on the appropriate flow charts.

In order to implement the Decision Tree the analyst merely starts at the top and proceeds down the appropriate branch dictated by the appropriate decision. The decisions are supplied by the answers to Table 4.4. The unknown vehicles signature is considered fully identified when the lowest point on the lowest branch is reached. To increase the level of confidence in his decision, the analyst is provided with a quick look summary of additional vehicle descriptors when he arrives at the lowest decision level.

To use the Matrix, the operator must, one row at a time, circle or fill in the appropriate decisions from Table 4.4 in the column of every vehicle that exhibits the characteristic in question. No

decision row or vehicle column may be overlooked if the Matrix approach is to succeed. Once the Matrix has been completed, vehicle identification is made by selecting the vehicle whose column has the highest percentage of its characteristic questions answered affirmatively.

#### 4.5.1 Example: Vehicle Classification

This section provides an example to demonstrate the application of each of these classification techniques.

In accordance with the instructions. The operator begins his analysis with a sonogram (Figs 12 and 13 were used for this example), Table 4.4 and multi-point dividers. The results of the use of Table 4.4 follows:

<u>Question</u>	<u>Answer</u>
1.	Strongest CFR = 6
2.	CFR 6 = 220 Hz
3.	CFR 1 = 35 Hz
4.	CFR 5, CFR 2, CFR 3
5.	No (AC between CFR 16 and 17)
6.	No (dominance pattern)
7.	No (20 consecutive CFR)
8.	DT 1 less than CFR 1
9.	DT 1 = 28.8 Hz
10.	DT 1 is very strong
11.	No chopped DT
12.	Yes (manual transmission: DT is mechanically coupled to engine)



13. DT 1 = CFR 1 = 0.82 (28.8/35)

14. Yes; accessory line between CFR 2 and 3

The next step is to use Table 4.5, "Decision Tree Technique", and the answers from Table 4.4. Then following Table 4.7:

a. The strongest CFR is not CFR-12

b. The strongest CFR is CFR-6

c. There is no accessory line between CFR 16 and 17

d. CFR-6 is greater than 135 Hz, therefore, vehicle is M-551, but for added assurance the confidence level questions can be answered.

e. Amplitude of DT 1 is nearly equal to that of CFR 6

f. CFR-5 is strong

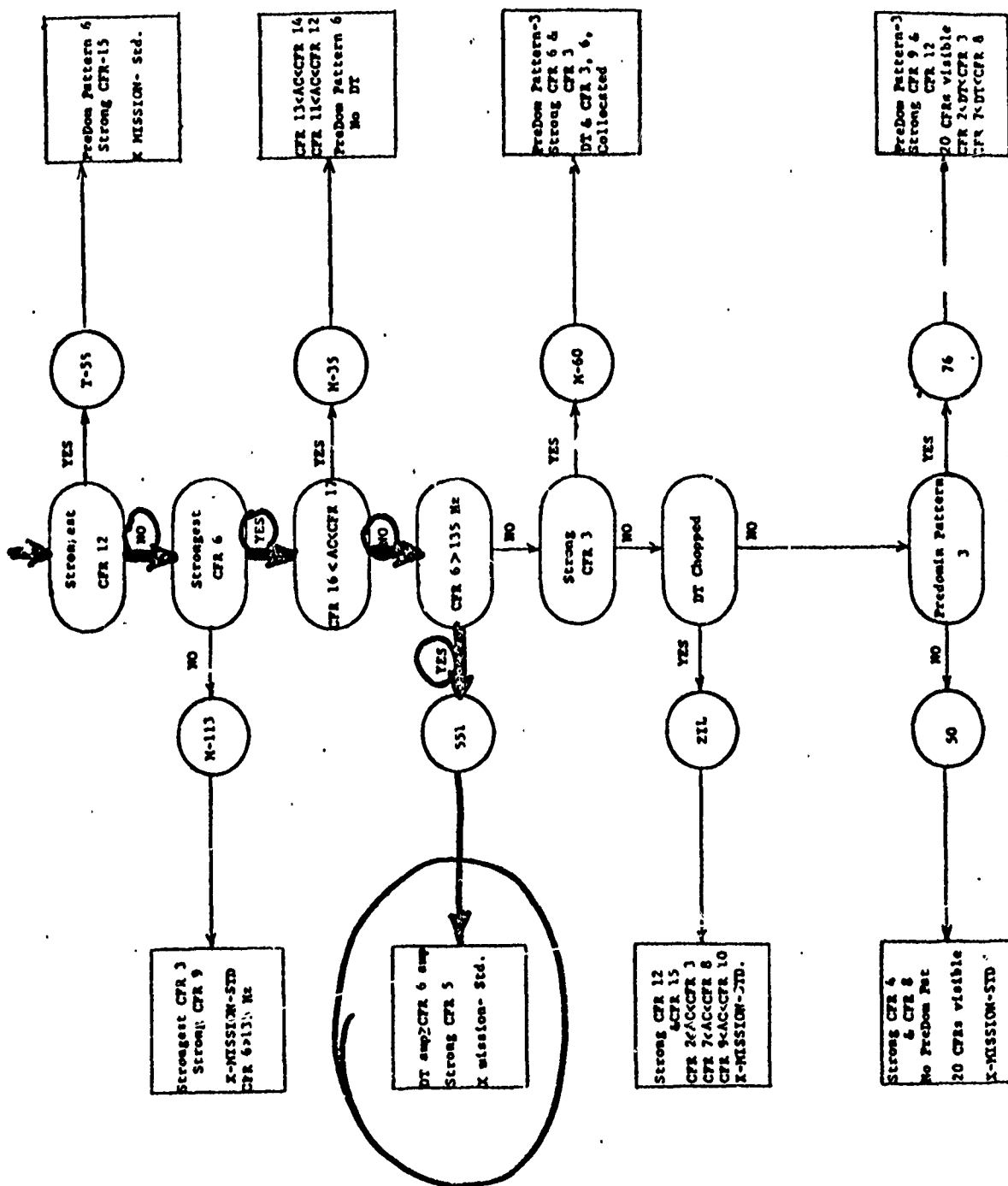
g. Vehicle has a standard transmission

h. The vehicle is definitely an M-551

3. Table 4.6, Vehicle Classification Matrix can also be used and a sample form, Table 4.8, has been completed. The results clearly show the vehicle to be an M-551 and also that the vehicle be in 2nd gear.

#### 4.6 Extended Analysis

The classification analysis was extended not only to techniques that were not line - description dependent but to those which used sensors other than acoustic. The extended techniques encompassed tread noise classification based on high frequency content and DEMON signature, seismic parameters to augment the acoustic methods, cube-law spreading to deliberately create a short range system, and pattern recognition methods based on correlation.



DECISION TREE  
TABLE 4.7

DISCRIMINANTS	VEHICLE		H 35					ZIL 157					M 113					M 551					BTR 50					PT 76					M 50					T 55				
	GEAR		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5					
STRONGEST CFR			6	6				6	6				3	3				6	6					6	6							6	6				12	12				
OTHER STRONG CFR	A		12	12				12	12				6	9				8	4					9	3							3	3				15	15				
TRANSMISSION TYPE								15	15				9					15	9					12													9	6				
STRONG DT ①			M	M				M	M				A	A				M	M					M	A							M	A				M	M				
PREDOMINANCE PATTERN			6	6																																						
ALL CFR'S TO CFR 20																																										
CFR 16 < AC < CFR 17 ②																																										
CFR 13 < AC < CFR 14			X	X																																						
CFR 11 < AC < CFR 12			X	X									X	X																												
CFR 7 < DT < CFR 8																																										
AC JUST BELOW CFR 6																																										
CFR 2 < AC < CFR 3																																										
DT < CFR 1																																										
CFR 1 < DT < CFR 2																																										
CFR 2 < DT < CFR 3																																										
CFR 3 < DT < CFR 4																																										
CFR 4 < DT < CFR 5																																										
AMPLITUDE DT ≥ CFR 6																																										
CFR 6 > 135 Hz.																																										
DT CHOPPED AND NOT CFR COINCIDENT																																										
RATIO DT 1 CFR 1 ③			4	6				4	31.8				1.8	0				0.8	0.4					2.5	1.4	3.0										2.9						

1 DT = DRIVE TRAIN LINE(S)  
 2 AC = ACCESSORY LINE  
 3 Variable for automatic transmission  
 4 No DT visible  
 5 No data  
 6 Discriminant absent  
 7 Discriminant present

3-12 4.8

#### 4.6.1 Tread Noise Classification

Tracked vehicles, especially heavy ones, generally can be recognized by the acoustic energy radiated by the track mechanisms. This energy is characterized both by being concentrated as a high-frequency carrier and by appearing as amplitude modulation of a corresponding noise-like carrier. Therefore two approaches have been implemented to classify tracked vehicles; one based on the carrier frequency energy and the other being DEMON.

##### 4.6.1.2 Tread Classification by Carrier Frequency Energy

The carrier frequency energy is believed to be caused by the treads rotating on their mounting pins thereby emitting squeaks and clanks when the vehicle is moving. This energy is strong enough to be recognized by the human ear. By prefiltering the analog signatures (1000 Hz high pass-approximately) these track sounds can be enhanced. For example, the UA-6 Ubiquitous Spectrum Analyzer on the 40 Hz resolution permitted a visual display of this energy on an oscilloscope. This energy is strongly modulated and sounds like repetitive squeaks or clanks but does not appear as a continuous function. Oscilloscope presentations have to be up-dated repeatedly to "catch" one or more of the clanks. Photographs shown in Figure 14 illustrate the results obtained from an M60 track signature.

##### 4.6.1.3 Tread Classification by DEMON

DEMON type processing proved useful and was successfully employed to detect four out of six tracked vehicle tread rates. DEMON is a demodulation scheme implemented for the purposes here as follows:

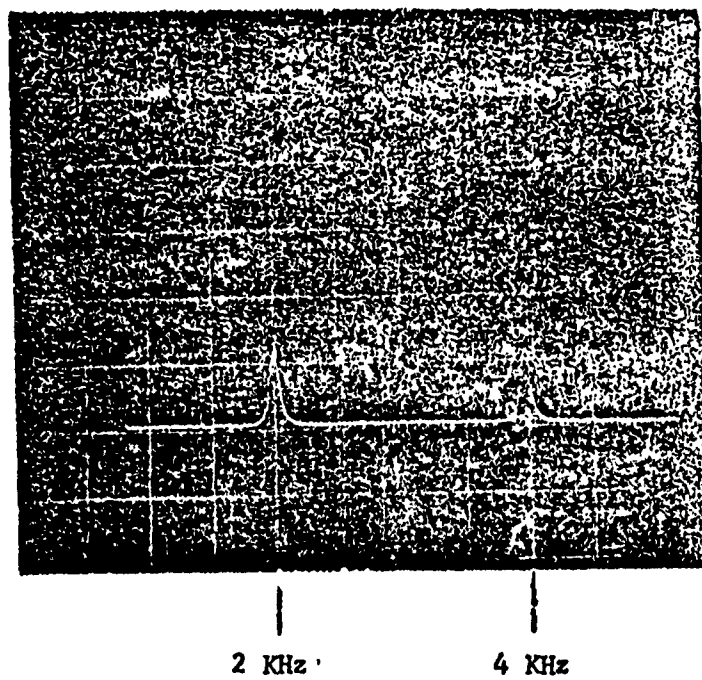


FIG. 14A - CALIBRATION

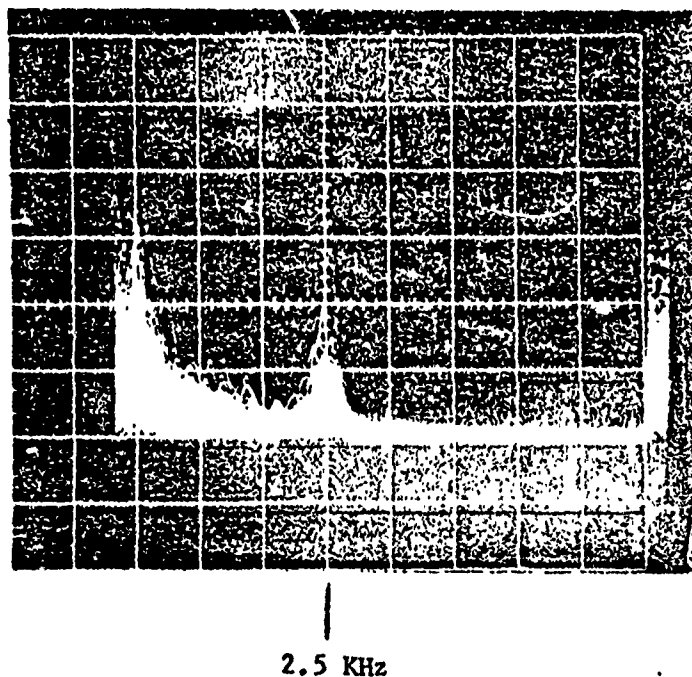


FIG. 14B - M-60 TANK AT 15 MPH

FIG. 14 - HIGH FREQUENCY TREAD ENERGY  
UBIQUITOUS SPECTRUM ANALYZER  
20 KHz RANGE - 40 Hz RESOLUTION BANDWIDTH

The signal is hi-pass filtered (700 Hz), diode detected ( $\frac{1}{2}$  wave), low pass filtered (50 Hz), A/D converted, and spectrum analyzed using an FFT computer algorithm. The computer analyzer used 1 Hz resolution over 64 Hz and performed signal averaging over an entire vehicle run. Other instrumentation techniques are feasible such as, using entirely analog devices or by combinations of analog and digital.

The following vehicles were classified as tracked by the DEMON procedure:

<u>Vehicle</u>	<u>Speed</u>	<u>Modulation Frequency Detected</u>
M 60	15 mph	40 Hz peak
M 60	7 $\frac{1}{2}$ mph	20
T 55	15	41
PT 76	7 $\frac{1}{2}$	24
BTR 50	15	32

It is believed that the modulation frequency detected by this technique corresponds to the tread rate or the rate at which the track shoes hit the ground. The following calculations show the tread rate for an M60 tank at 15 mph:

$$\text{Velocity} = \text{distance traveled/sec} = 22 \text{ ft/sec} \times \frac{12 \text{ inches}}{\text{foot}}$$

$$\begin{aligned} \text{No sprocket teeth} &= \text{No. shoes hitting ground per revolution} = 11 \\ \text{Pitch dia.} &= 2 \times \text{effective radius from sprocket axle to shoes} \\ &= 24.5 \text{ inches} \end{aligned}$$

$$\begin{aligned} \text{No shoes/sec} &= \frac{\text{distance traveled/sec}}{\text{distance around sprocket}} \times \frac{\text{No. shoes}}{\text{rev.}} \\ &= \frac{22 \times 12}{24.5} \times 11 \\ &= 37.8 \text{ shoes/sec} = \text{tread rate} \end{aligned}$$

A summary of the calculated tread rates is shown below:

<u>Vehicle</u>	<u>Speed</u>	<u>Calculated tread rate</u>
M 60	15 mph	37.8 Hz
M 60	7½	18.9
T 55	15	48.0
PT 76	7½	26.4
BTR 50	15	52.7
BTR 50	7½	26.4

The resulting agreement for the PT 76 at 7½ mph, the M 60 at 15 mph and to some extent the T 55 at 15 mph suggest that this is in fact, a believable result. However, the poor result of the BTR 50 calculated shoe rate compared to the detected frequency is as yet unexplained. Figures 15 through 22 are the ensemble averages of typical vehicle runs for each type of vehicle. They show the peaking at the tread rate modulation frequency. Note that the scale is 40 db/inch to achieve wide dynamic range in the print-out, therefore peaking of the order of ½ inch corresponds to 10 db and is significant.

#### 4.6.2 Seismic Data Analysis

Enlargement of the data base to include more vehicle types may require the inclusion of additional sensor data than just acoustic. The seismic sensor was selected because the observed signals can be related to the physics of the seismic radiation from the vehicle and such relations are extremely important in establishing credibility for the classification techniques. Equally important, the seismic data complements the acoustic data in evaluating line structure and line families.

# PLOT OF POWER SPECTRUM VS. FREQUENCY

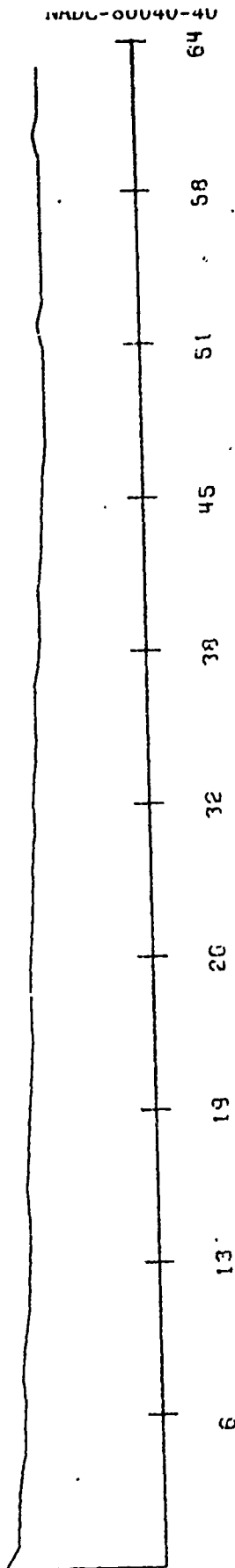
REEL NO. 5 DETECTOR

VEH M-35

TIME

HH/MM/SS

0: 0: 0



FREQ. - HZ.

SAMPLING RATE = 128 HZ

VERTICAL SCALE = 40 DB/IN

RESOLUTION = 1.00 HZ

SAMPLE SIZE = 128 PTS

FIG 16



# PLOT OF POWER SPECTRUM VS. FREQUENCY

REEL NO. 9 DETECTOR

VEH M-551

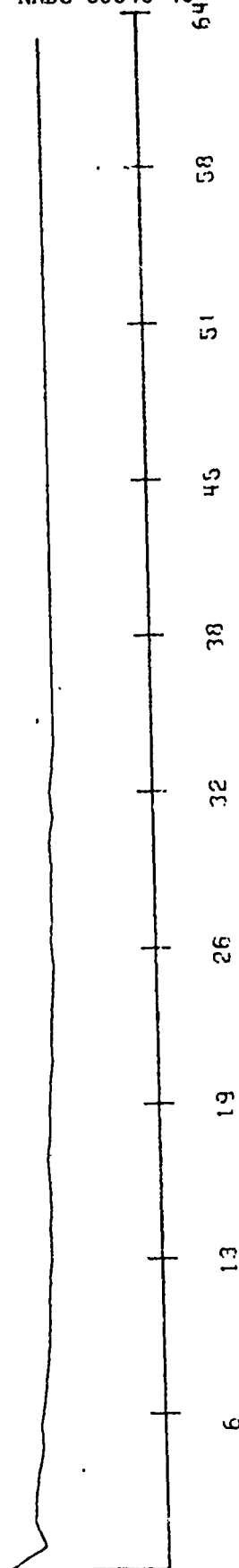
TIME

HH/MM/SS

0:0:0

C-45

NADC-80040-40



FREQ. - HZ.

RESOLUTION= 1.00 HZ

SAMPLE SIZE: 128 PTS

SAMPLING RATE = 128 HZ

VERTICAL SCALE = 40 DB/IN

FIG 15

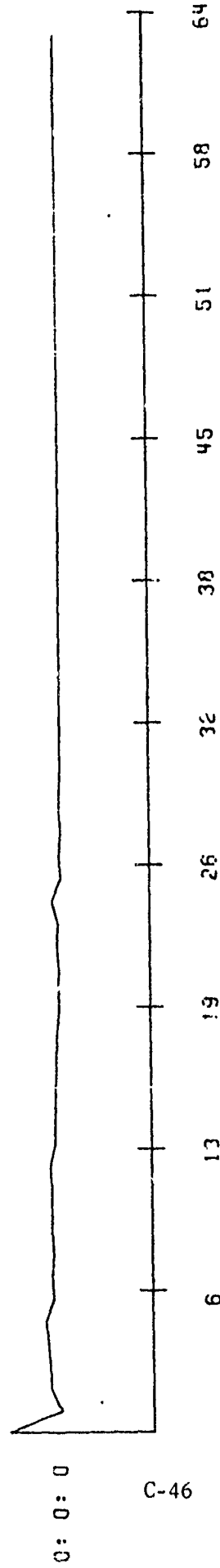
# PLOT OF POWER SPECTRUM VS. FREQUENCY

REEL NO. 27 DETECTOR

VEH PT-76

TIME

HH/MM/SS



FREQ. - HZ.

SAMPLING RATE = 128 HZ

VERTICAL SCALE = 40 DB/IN

RESOLUTION = 1.00 HZ

SAMPLE SIZE = 128 PTS

FIG 17

# PLOT OF POWER SPECTRUM VS. FREQUENCY

REEL NO. 11 DETECTOR

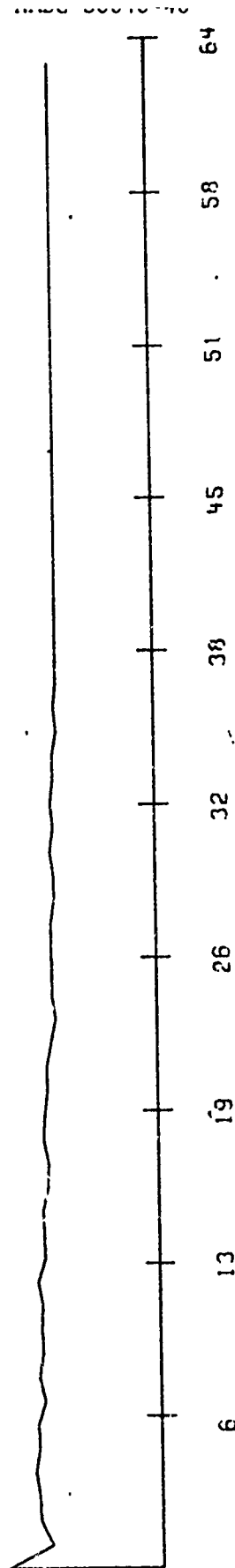
VEH MI13AI

TIME

HH/MM/SS

0:0:0

C-47



FREQ. - HZ.

SAMPLING RATE = 128 HZ

VERTICAL SCALE = 40 DB/IN

RESOLUTION = 1.00 HZ

SAMPLE SIZE = 128 PTS

FIG 18

# PLOT OF POWER SPECTRUM VS. FREQUENCY

REEL NO. 17 DETECTOR

VEH BTR-50

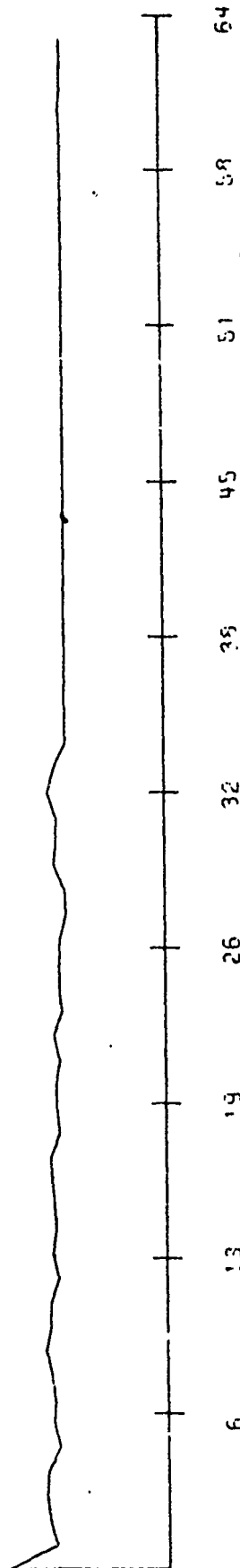
TIME

HH/MM/SS

0: 0: 0

C-48

NADC-80040-40



FREQ - - HZ

SAMPLING RATE = 128 HZ  
VERTICAL SCALE = 40 DB/IN

RESOLUTION = 1.00 HZ  
SAMPLE SIZE = 121 PIS

FIG 19

# PLOT OF POWER SPECTRUM VS. FREQUENCY

REEL NO. 18 DETECTOR

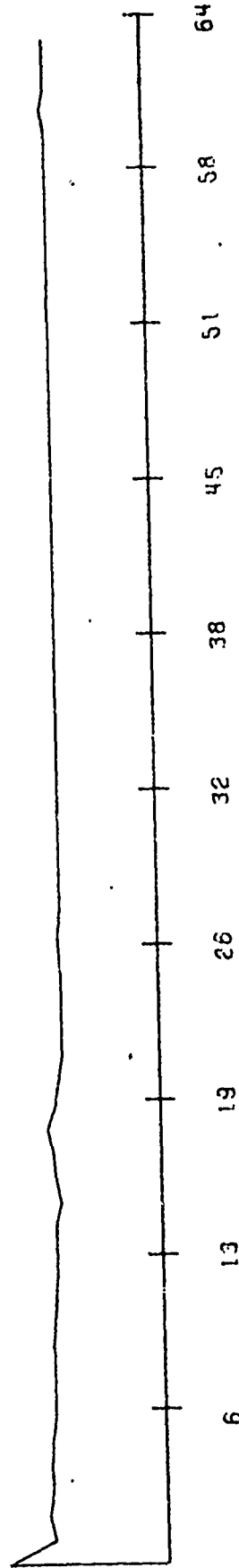
VEH M-60

TIME

HH/MM/SS

0:0:0

C-49



FREQ. - HZ.

SAMPLING RATE = 128 HZ

VERTICAL SCALE = 40 DB/IN

RESOLUTION = 1.00 HZ

SAMPLE SIZE = 1.8 PTS

FIG 20

# PLOT OF POWER SPECTRUM VS. FREQUENCY

REEL NO. 19 DETECTOR

VEH M-60

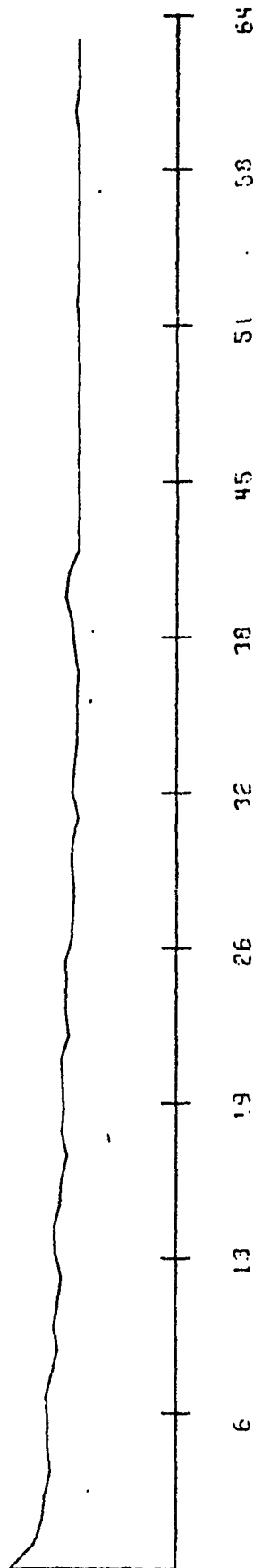
TIME

HH/MM/SS

0:0:0

C-50

NADC-80040-40



FREQ. - HZ

SAMPLING RATE = 128 HZ  
VERTICAL SCALE = 40 DB/IN

RESOLUTION = 1.00 HZ  
SAMPLE SIZE = 1.00 SEC

FIG 21

# PLOT OF POWER SPECTRUM VS. FREQUENCY

REEL NO.23 DETECTOR

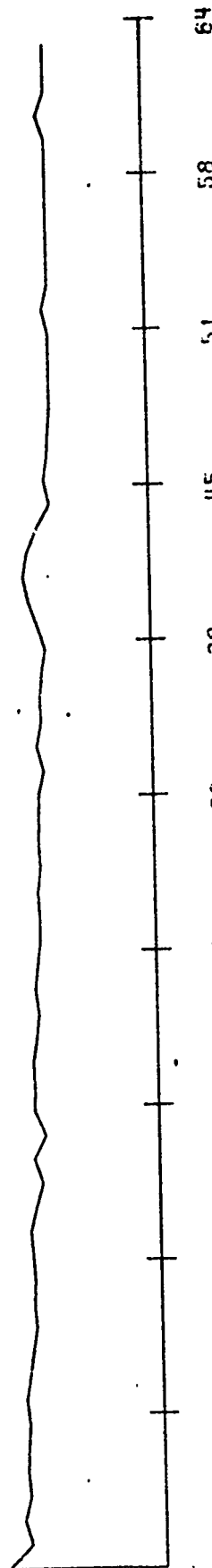
VEH T-55

TIME

HH/MM/SS

0:0:0

C-51



FREQ. - HZ

SAMPLING RATE = 128 HZ  
VERTICAL SCALE = 40 DB/IN

RESOLUTION = 1.00 HZ  
SAMPLE SIZE = 129 PTS

#### 4.6.2.1 Seismic Data

The seismic data shows both broadband noise energy and line energy similar to that obtained for the acoustic data but, of course, for much shorter ranges. A full evaluation based on generating descriptors for the broadband energy and an amplitude comparison of line strengths has not yet been made so that the results are fragmentary.

#### 4.6.2.2 Seismic-Acoustic Interaction

A vehicle moving over the ground will radiate acoustic waves in the air and seismic waves in the ground. The acoustic waves are characterized by a family of harmonically related engine rate lines from which the number of cylinders and the engine rate can be evaluated. If this engine rate family is then extracted from the total acoustic signal, there remains, in general, another harmonically related family of lines, unrelated lines, and broadband energy.

The remaining harmonically related family is associated with the wheels and/or tracks of the vehicle. For the wheeled vehicle examined in detail, this second set is missing. The initial conclusion is that this second set is a good tracked/wheeled discriminator.

The seismic waves are generated by the vehicle motion over the ground. Their strength depends upon the coupling between the vehicle and the ground. The principle source of the air waves appears to be the engine. During the present experiment, seismic waves were detected from a track vehicle by a seismometer sensitive to vertical particle



motion as well as by two (2) seismometers sensitive to horizontal particle motion. The horizontal component seismometers were oriented to detect vibrations, parallel and perpendicular to the line of movement of the vehicle. An analysis of the waves detected by the seismometers showed that the spectrum of the waves detected by the two horizontal component seismometers were considerably different, but that all three seismometers detected a strong motion at about 25 Hz, out to the maximum range of the vehicle. Such variations of the spectrum of particle motion in two horizontal directions may provide a useful method of differentiating between track and wheeled vehicles, when this system includes an acoustic sensor as well. The reason is that the transmission family of lines is identifiable in the seismic data.

It should also be pointed out that acoustic waves in the air also generate seismic waves and that seismic waves generate air waves. Coupling between air waves and seismic waves was observed in the present experiment. The reverse coupling was not observed, but it may be important if the acoustic detector is behind an obstruction or in a heavily wooded area. Seismic waves offer an advantage when the air waves are weak.

It is well known from seismic experiments with explosives that a very strong resonance coupling between air waves and seismic surface waves of the Rayleigh type will occur when the shear waves of the near surface layer is sufficiently below the speed of sound in air. These strong coupled waves are called air-coupled Rayleigh waves. They

exhibit retrograde elliptical particle motion and follow the air wave in time as a constant frequency train of waves. The frequency of these waves corresponds to the frequency at which the acoustic velocity in the air and the seismic velocity in the ground are equal. The reverse coupling can also be observed in general, although these air-coupled Rayleigh waves were not observed on this data base.

The system problem generated by this cross coupling can be readily handled. The acoustic engine line family has a large amplitude and almost always couples into the seismic lines because they are at the same frequency as the engine acoustic lines. Similarly, frequency comparison of the transmission/track lines of both the acoustic and seismic signals then aids this line identification.

#### 4.6.3 Cube-Law Spreading

Cube-Law Spreading is an interesting technique for reducing the effect of aircraft on signatures and for counting and separating vehicles in a convoy as they pass nearby the sensor. The system is instrumented by using the outputs of two closely spaced microphones to generate, functionally, two power spectrums vs time plots which are then subtracted from each other. The incoherent subtraction process in effect causes differentiations of the propagation law so that inverse square law losses become inverse cube law. The result is a system which is square-law in the normal long range mode, switchable on command to the shorter range cube law system.

Two further features are present. In addition to the cube law loss which is effective against aircraft at long ranges, the equivalent microphone response of the composite system becomes that of a gradient so that the system is effective in reducing both the direct and ground reflected rays from nearby, overhead aircraft. By using more microphones, the propagation loss can be increased - e.g. two microphones give inverse cube law, three give inverse quadratic law ..., etc., to any degree permitted by the ambient noise level and the dynamic range of the equipment.

This technique has been instrumented on a computer with real data and performs as predicted. The range filtering is real. Given two radiators, even at the same bearing, the signal from the far range radiator is attenuated compared to the near range radiator. The additional attenuation due to the cube-law behavior is, of course  $10 \log$  of the range ratio. The absolute attenuation for a sensor at a particular range is  $10 \log$  of the ratio of the range to the microphone spacing, plus the normal spherical ( $20 \log$ ) spreading loss and the pattern attenuation associated with a gradient microphone.

#### 4.6.4 Vehicle Classification by Correlation

Correlation, as a vehicle classification technique, was examined from the point-of-view of utilizing reasonable pattern recognition methods in both the frequency domain and the time domain. Both approaches were explored using a digital computer.

##### 4.6.4.1 Frequency Domain Correlation

The intent here is to compare the power spectra of the same and different vehicles by cross correlation. The basis of the

technique is that the line patterns of the same vehicle should match if allowance is made for the effects of vehicle speed. This allowance is made by using the log of the frequency instead of frequency as the independent variable.

The next problem is to avoid correlations based on a single strong line. This is accomplished by dynamic range compression which is simply done by using a dB scale instead of a linear scale. Further compression can be done, if necessary, by using a dB squared scale (dB of the dB). Two problems remain. The first of these is that the power spectrum is a positive function and the correlation of two positive functions always has a high correlation coefficient. To avoid this the average value of the power spectrum is set to zero before correlation.

The remaining problem is line frequency sensitivity - i.e. small random shifts in the frequencies of the lines greatly effecting the correlation coefficient. Initial attempts were made with ten frequency bin averaging. A moderate success was achieved (60 per cent correct classification). The data shows that this degree of averaging is too much and fewer bins should be used.

The details of the frequency domain correlation process is to start with a sample of an unknown vehicle signal. This is transformed by the FFT algorithm and the digitized spectrum entered into the computer. The frequency scale is compressed logarithmically with the

power ratios averaged over adjacent frequencies and then converted to decibels (dBs). A correlation is next performed against each of the signatures in the vehicle library. This resulting data is stored and the entire process repeated with the next block of data from the unknown vehicle signature. The result is then cumulatively averaged with the previous set of results. When sufficient blocks of data have been entered, the vehicle in the library with the highest correlation result is selected as the best match to provide the identification required. In order to avoid false classification the magnitude of the best match must be greater than 0.85 at its peak value.

Implementation of the above program has not yet been completed. Preliminary tests using samples from stake 2 and stake 9 of 15 mph runs for 7 vehicle signatures have been done. However, no cumulative averaging was included, therefore the results were not optimum. Of these signatures, three were successfully classified and a fourth came out second best. These were considered encouraging enough results to carry on with the development of this program.

#### 4.6.4.2 Time Domain Correlation

Time domain correlation is similar to frequency domain correlation except no FFT is involved. The results here are not definitive enough even for preliminary comments.

#### 4.7 Computer Assisted Classification Technique

The classification technique developed in this report employs either a Decision Tree or a Matrix and a questionnaire to present the data base to the operator. The operator is then required to follow the Decision Tree, or fill out the Matrix, match it against the data base questionnaire to make the vehicle identification. In order to simplify this process, both the data base and the answers to the questionnaire were formalized into matrices and then matrix matching was performed to classify the vehicle. Since considerable computation is required for the formal matrix matching technique, a computer program was written which constructs the vector corresponding to the unknown vehicle, then using the data base, performs the necessary computation, and selects the best match to identify the unknown vehicle. The development of the matrix matching technique and its application with the computer are presented in Appendix 1.

## 5.0 ACKNOWLEDGEMENTS

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APPENDIX 1

COMPUTER-ASSISTED CLASSIFICATION TECHNIQUE



## 1. INTRODUCTION

A surface vehicle signature analysis program was undertaken based on a LAVA system for signal processing. Interpretation of the LAVA-grams was followed by vehicle discriminant selection, establishment of an acoustic signature data base, and determination of the classification procedure.

The resulting classification procedure is suitable for fully automatic techniques, an expressed Task III goal of the Mystic Mission program. The application of this procedure to 18 sample LAVA-grams resulted in 100% correct vehicle identification.

## 2. DATA REDUCTION

The LAVA is an NADC development system which displays power spectrum vs time in a graphic form (LAVA-gram) analogous to that of the standard Navy LOFAR gram. It has options as to bandwidths, frequency resolution, and frequency translation obtainable with conventional gear.

The LAVA-grams obtained were analyzed and reasonable classification discriminants extracted. These classification discriminants are listed in Table A-1. A more detailed description is given below:

1. The ratios of the harmonic numbers of the stronger cylinder firing rate (CFR) lines. These are obtained by observing:

- a. The harmonic number of the strongest cylinder firing rate (CFR) line.

- b. The harmonic numbers of other strong cylinder firing rate (CFR) lines.

2. The transmission type, manual (M) or automatic (A), as determined by the corresponding or noncorresponding tracking in frequency of the cylinder firing rate lines (CFR) and the drive train lines (DT).

3. The presence of a high intensity drive train line (DT).

4. The predominant harmonic pattern - e.g., whether the intensity pattern repeats over every six harmonic lines or over every three harmonic lines.

5. The presence or absence of at least 20 consecutive harmonics of the cylinder firing rate lines.

6. The presence or absence of accessory equipment lines relative to the following cylinder firing rate (CFR) lines:

- a. Between CFR 16 and CFR 17.\*
- b. Between CFR 13 and CFR 14.
- c. Between CFR 11 and CFR 12.
- d. Between CFR 2 and CFR 3.
- e. Just below CFR 6.

7. The presence or absence of drive train lines relative to the following cylinder firing rate lines:

- a. Between CFR 7 and CFR 8.
- b. Below CFR 1.
- c. Between CFR 1 and CFR 2.
- d. Between CFR 2 and CFR 3.
- e. Between CFR 3 and CFR 4.
- f. Between CFR 4 and CFR 5.

8. The amplitude of the drive train line; whether greater or less than the amplitude of the sixth harmonic of the cylinder firing rate line.

9. The frequency of the sixth harmonic of the cylinder firing rate line; whether greater or less than 135 Hz.

10. The presence or absence of a drive train line which is chopped and does not coincide with a cylinder firing rate line.

The problem remains to numerically describe these discriminants, for the known vehicles of the data base and the target vehicle to be identified and then to combine these numerical values into a single numerical value for each vehicle type. The vehicle accepted as present is the one with the corresponding highest numerical value. Ties are possible.

### 3. BASIS OF THE CLASSIFICATION PROCEDURE

#### The Classification Procedure is Based on:

1. Structuring the known vehicle data base. By this is meant that the LAVA-grams for each known vehicle type are examined for the discriminants shown in Table A-1 and numerical

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\* The notation "CFR 16" denotes the sixteenth harmonic of the cylinder firing rate. UNCLASSIFIED.

values are assigned to the presence or absence of each discriminant. The assignment is + 1, (or zero if the absence of a discriminator is not significant.)

The end result is a matrix. Each column represents a vehicle type, each row a descriptor. A particular vehicle type may be represented in more than one column if it has more than one set of descriptors corresponding to different operating conditions. This matrix will be called the Vehicle Characteristic Matrix.

2. Structuring the signature of the target vehicle. By this is meant that the LAVA-gram for the target vehicle is examined for the discriminants shown in Table A-1 and numerical values (+ 1 or 0) are assigned to the presence or absence of each discriminator. The result is presented as a single row matrix.

3. Devising a combination rule for the vehicle characteristic matrix and the row matrix of the target vehicle. The vehicle characteristic matrix specifies each descriptor for each vehicle. The row matrix of the target vehicle describes in a single row matrix form the presence or absence of each discriminator in the unknown signature. These two matrices are combined by matrix multiplication.

For each vehicle the end number is the sum of the products of the data descriptors and the unknown's descriptors. The final vehicle numbers are compared and the highest number gives the most likely vehicle type. If there is a tie then two equally likely answers are obtained. This technique is recommended since it formalizes the comparison of matrices.

#### 4. DETAILED DEVELOPMENT OF THE CLASSIFICATION PROCEDURE

To use this classification procedure it is necessary to:

1. Structure the data base from the vehicle characteristic table.

2. Structure the signature of the unknown as a row matrix.

3. Combine the two matrices by multiplication into a matrix of numerical identifiers. The greatest numerical value identifies the vehicle type present.

The details of this procedure will be presented using matrix notation for the structuring of the data base and the signature of the unknown. The combination procedure will then be matrix multiplication.

#### 4.1 Matrix Construction Rules

Rows of the vehicle characteristic matrix represent descriptors, columns represent vehicle types. The discriminants of the reference data base must be numerically structured according to the importance of the data as discriminators. The rules for converting the three characteristic types to matrix form are:

TYPE I. The characteristic described by the line is evaluated only for its presence or absence. The presence of the characteristic provides valuable information. The information value of its absence is neutral; that is, no conclusion may be drawn from it. This type of characteristic should be represented in the matrix by + 1 for each vehicle where it is present and by 0 if it is absent.

TYPE II. The characteristic described by the line is evaluated for its presence or absence; either its presence or its absence provides valuable information. In this case the characteristic is represented in the matrix by + 1 if present and by - 1 if not.

TYPE III. The characteristic as described by the line may assume one of  $k$  possible numerical values. (If only two numerical values are possible, then + 1 and - 1 may be used to represent them.) If more than two values occur, (as in the ratio of the strongest line frequency to the next strongest line frequency) more than one row is needed. The easiest course to follow is to use each row to separate the number of possible values into two nearly equal sets using the values + 1 and - 1 to perform the separation, so that if  $k$  different values are possible, at most  $\log_2 k$  rows are used to isolate those values.

When the data base is converted into matrix form, each characteristic of Type I and II will contribute one row to the matrix, while characteristics of Type III may contribute as many as four or five rows.

Vehicles having only one set of operating characteristics, therefore, only one signature, are represented by a single column of the matrix, while vehicles with multiple signatures are represented by one column for each possible signature.

#### 4.1.1 Illustration of Vehicle Characteristic Matrix

Each column of the Vehicle Characteristic Table (Table A-1) contains one or more unique signatures. For example, the PT-76 amphibious tank has the sixth harmonic of the cylinder firing frequency appear as the highest intensity CFR line on the LAVA-grams. The second highest intensity CFR line may be either the 9th or 12th harmonic of the cylinder firing frequency. Therefore two CFR ratios (6/9 or 6/12) are possible, so that this one column of Table A-1 contains two distinct signatures, and will be represented in two columns of the Vehicle Characteristic Matrix.

The assignment of vehicle operating characteristics as Types I or II is based on engineering judgement, made when the raw data (in this case LAVA-grams) are analyzed to form the data base. Operating characteristics which have more than two numerical values are automatically classed as Type III. For example, the presence or absence of a drive train line between CFR 3 and CFR 4 is treated as a Type I characteristic. The column representing the M-551 in fourth gear, the BTR-50 in fourth gear, and the M-60 in high gear will have + 1 in the appropriate row of the Vehicle Characteristic Matrix. All other columns in that row will have the number zero entered in them. The question concerning the frequency of CFR 6, i.e., less than or greater than 135 Hz is treated as a Type II characteristic; for those signatures where CFR 6 is less than 135 Hz - 1 is entered in the matrix, while CFR 6 greater than 135 Hz is noted by + 1.

The ratios of the harmonic numbers of the highest intensity to the second highest intensity cylinder firing frequencies in this data base have ten distinct values, ranging from 0.33 to 2.0. To distinguish between 10 different values of a characteristic, it has to be treated as Type III, and it requires four rows of the Vehicle Characteristic Matrix. These four rows are constructed from the following master matrix.

Row	Ratios									
	.33	.4	.5	.66	.75	.8	1.2	1.33	1.5	2.
1	1	1	1	1	1	1	1	1	-1	-1
2	1	1	1	1	-1	-1	-1	-1	-1	1
3	1	1	-1	-1	-1	-1	1	1	1	1
4	1	-1	-1	1	1	-1	-1	1	1	1

where each numerical value is represented by a unique sequence of +1's and -1's. All signatures which have a CFR ratio of .75 will have the numbers +1, -1, -1, +1 in the first four rows of the corresponding column of the Vehicle Characteristic Matrix. The ratio of the drive train fundamental frequency to the cylinder firing rate fundamental frequency is treated similarly.

Using the rules outlined and illustrated above, the Vehicle Characteristic Table (Table A-1) was converted to the Vehicle Characteristic Matrix, which is presented in Table A-3. The legend for the rows of the matrix and the characteristic types are given in Table A-2.

#### 4.1.2 Weighting the Vehicle Characteristic Matrix

For further discussion let the Vehicle Characteristic Matrix be called matrix A. For completeness, A has m rows and n columns, with elements  $a_{ij}$  ( $i = 1, m; j = 1, n$ ). As constructed, each of the  $a_{ij}$  has a numerical value of +1, -1, or 0.

It may be desirable to be able to weight each element of this matrix on the basis of its relative importance as a discriminator (or alternatively, on the confidence that may be attached to the presence or absence of the corresponding characteristic). To accomplish this, each row of matrix A is multiplied by an arbitrary weight by  $w_i$  (for the  $i$ th row). Note that weighting by the importance of characteristics is optional.

A further weight is required when two or more rows are used to represent a single Type III operating characteristic. This weight balances the undue weight implied by the multiple rows used for a single characteristic. Its value should be the reciprocal of the number of rows used to represent the Type III characteristic. These weights, denoted by  $s_i$  for the  $i^{\text{th}}$  row, are used to multiply each element in the appropriate row of matrix A. The elements of the weighted matrix, denoted as matrix B, has elements  $b_{ij}$  given by:

$$b_{ij} = a_{ij} \cdot w_i \cdot s_i \quad \begin{matrix} i=1, \dots, m \\ j=1, \dots, n \end{matrix}$$

The only weights which must be applied to the Vehicle Characteristic Matrix of Table A-3 are those due to multi-valued parameters. Using weights developed as discussed above, a Weighted Vehicle Characteristic Matrix is developed; it is presented as Table A-4. (The legend of Table A-2 also applies to this latter table.)

### 1.1.3 Normalizing the Weighted Vehicle Characteristic Matrix

The next step is to normalize the Weighted Vehicle Characteristic Matrix. Calling the normalized matrix C, with elements  $c_{ij}$ , the normalization is accomplished by the following equation:

$$c_{ij} = b_{ij} / \left( \sum_{r=1}^m b_{rj}^2 \right)^{1/2}$$

The Normalized Vehicle Characteristic Matrix, matrix C, is presented in Table A-5. The legend shown in Table A-2 also applies to this latter table.

### 4.2 Target Vehicle Matrix

To use the classification matrix C given in Table A-5, each of the characteristics of the unknown vehicle has to be determined and converted to a form compatible with matrix C. The required form is that of a row vector (hereafter called vector Z) with elements  $z_j$ . Z is constructed according to rules specified below, which are complementary to the rules used to construct the Vehicle Characteristic Matrix.

First, calculate the ratio of the harmonic numbers of the two strongest CFR lines, and denote this number by R. Then:

If $R > 1.4$	$z_1 = -1$ ; otherwise $+1$ .
If $.7 \leq R < 1.75$	$z_2 = -1$ ; otherwise $+1$ .
If $.45 \leq R < 1.00$	$z_3 = -1$ ; otherwise $+1$ .
If $.36 \leq R < .58$ OR $.77 \leq R < 1.27$	$z_4 = -1$ ; otherwise $+1$ .

If transmission type is:

Manual	$z_5 = +1$
Automatic	$z_5 = -1$
Unknown	$z_5 = 0$

If there is a strong drive train line present, let

$z_6 = +1$ ; otherwise, let  $z_6 = 0$ .

If the predominance pattern is 3, let  $z_7 = +1$ ;  
if it is pattern 6, let  $z_7 = -1$ ;  
if the pattern is indeterminate, let  $z_7 = 0$ .

If all CFR's up to CFR 20 are present, let  $z_8 = +1$ ;  
otherwise, let  $z_8 = 0$ .

If accessory lines are present:

Between CFR 2 and 3	$z_9 = +1$ ; otherwise 0.
Between CFR 5 and 6	$z_{10} = +1$ ; otherwise 0.
Between CFR 11 and 12	$z_{11} = +1$ ; otherwise 0.
Between CFR 13 and 14	$z_{12} = +1$ ; otherwise 0.
Between CFR 16 and 17	$z_{13} = +1$ ; otherwise 0.



If drive train (DT) lines are present:

Below CFR 1	$z_{14} = +1$ ; otherwise 0.
Between CFR 1 and 2	$z_{15} = +1$ ; otherwise 0.
Between CFR 2 and 3	$z_{16} = +1$ ; otherwise 0.
Between CFR 3 and 4	$z_{17} = +1$ ; otherwise 0.
Between CFR 4 and 5	$z_{18} = +1$ ; otherwise 0.
Between CFR 7 and 8	$z_{19} = +1$ ; otherwise -1.

If the amplitude of DT  $\geq$  CFR 6, let  $z_{20} = +1$ ; otherwise, let  $z_{20} = 0$ .

If CFR 6  $> 135$  Hz, let  $z_{21} = +1$ ; otherwise, let  $z_{21} = -1$ .

If the DT line is chopped and not CFR coincident, then  $z_{22} = +1$ ; otherwise  $z_{22} = 0$ .

Calculate the frequency ratio of DT 1 to CFR 1; denote the ratio by Q. Then:

If $Q > 2.9$	$z_{23} = -1$ ; otherwise +1.
If $1.45 \leq Q < 3.6$	$z_{24} = -1$ ; otherwise +1.
If $0.9 \leq Q < 2.2$	$z_{25} = -1$ ; otherwise +1.
If $0.4 \leq Q < 1.2$ OR	
$1.6 \leq Q < 2.6$ OR	
$3.2 \leq Q < 4.1$	$z_{26} = -1$ ; otherwise +1.

The row vector Z thus constructed is conformable with the Vehicle Characteristic Matrix A. Before use, the vector Z has to be made compatible with the Weighted, Normalized Matrix C. The weights applied to matrix A have to be applied to the vector Z. The weight used for the first row of matrix A is used for the first element of row vector Z, and so on. The weighted vector Z is normalized to form vector X, with elements  $x_j$  given by:

$$x_j = z_j w_j s_j / \left[ \sum_{k=1}^m (z_k w_k s_k)^2 \right]^{1/2}$$

#### 4.3 Vehicle Identification

The comparison of the signature of the unknown vehicle with the known signatures, represented by the row vector  $X$  and matrix  $C$  respectively, can be accomplished by matrix multiplication; letting this product be denoted by  $Y$ :

$$Y = XC$$

and the elements of  $Y$  are, of course, given by:

$$y_j = \sum_{k=1}^m x_k c_{kj}$$

Since the vector  $Y$  is the product of normalized matrices, it has the property

$$-1 \leq y_j \leq +1 \quad (j=1, \dots, n).$$

A column of matrix  $C$  can be viewed as a point in  $n$ -space, representing a particular vehicle. The vehicle to be identified is also a point in that space, and is characterized by vector  $X$ . Then the value of  $y_j$  is the directional cosine of the angle between the column vector  $(c_{1j}, c_{2j}, \dots, c_{mj})$  and the row vector  $(x_1, x_2, \dots, x_m)$  for each  $j$ .

The value  $y_j=1$  will occur if and only if the vector of the characteristics of the unknown vehicle matches exactly the  $j$ th column of the matrix of known vehicle behavior characteristics. If none of the  $y_j$  are equal to 1, then the signature of the unknown vehicle does not match any signature in the data base exactly. In that case, the vehicle whose column yielded the largest rank (i.e., the largest value) in the vector  $Y$  should be identified as the source of the unknown signature.

## 5. CLASSIFICATION PROCEDURE

The classification procedure is simple in concept; the characteristics of the known vehicles of the data base are numerically described in a matrix, the characteristics of the target vehicles are observed, listed, and converted to matrix form. Then the two are combined as a weighted sum - formally by a simple matrix multiplication. When only a small number of vehicles comprise the data base, manual computation is feasible, but any appreciable increase in the number of vehicles greatly increases the number of multiplications and additions to be done. Of course, a simple digital processor could handle this computation whose complexity is just mere size.

To demonstrate feasibility and to enable a complete checkout of the technique, a computer program was written (in FORTRAN) to accomplish the task in the following order.

- a. Read from a file and Vehicle Characteristic Matrix (Matrix A) and the weights.
- b. Weight and normalize the test matrix to obtain the weighted, normalized, Vehicle Characteristic Matrix C.
- c. Present to the operator the questions that have to be answered to classify an unknown vehicle.
- d. Accept the answers, one at a time, either as numbers or as yes/no, as appropriate.
- e. With the built-in logic, construct the row matrix Z which describes the target vehicle.
- f. Weight and normalize the matrix Z to obtain vector X and perform the matrix multiplication  $Y = XC$ .
- g. Select the largest element of vector Y, find the identifier of the corresponding vehicle, and display both.

Figure A-1 shows a sample of the program output. The FORTRAN program is given in Figure A-2. The input file actually used for vehicle classification in this exercise is given in Figure A-3. (The rules for the construction of the input file are given in Figure A-4.)

The computer program is written to be readily usable with a data base built on a large number of vehicle types. The program has the advantage of eliminating all of the manual computation and multiple decision processes used to construct the unknown vehicle characteristic matrix. Application of the program should result in high classification rates at low levels of error. The program is adaptable to a completely automated vehicle classification technique, where all signals processed could be passed to the classification program without human intervention.

To test the interactive classification technique unidentified LAVA-grams were read to determine the operating characteristics of unknown vehicles. In a sample of 18 LAVA-grams 100% correct vehicle identification was achieved.

TABLE A-1 VEHICLE CHARACTERISTIC TABLE

DISCRIMINANTS	VEHICLE		M 35				ZIL 157				M 113				M 551				BTR 5				PT 74					M 60	T 55																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																						
	GEAR		1	2	3	4	1	2	3	4	5	1	2	3	1	2	3	4	5	1	2	3	4	5	LO	HI	1	2		3	4	5																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																			
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① DT = DRIVE TRAIN LINE(S)  
 ② AC = ACCESSORY LINE  
 ③ DT = DRIVE TRAIN LINE(S)  
 ④ AC = ACCESSORY LINE

① Variable for automatic transmission  
 ② No DT visible

① Discriminant absent  
 ② Discriminant present

① No data

TABLE A-2 LEGEND FOR TABLES A-3, A-4, AND A-5

DISCRIMINANT	TYPE CHARACTERISTIC	NUMBER OF ROWS REQUIRED	MATRIX ROWS
The ratio of the harmonic numbers of the two highest intensity cylinder firing rate lines.	III	4	1-4
The type of transmission (manual or automatic).	II	1	5
The presence or absence of a high intensity drive train line.	I	1	6
The presence or absence, and nature of the predominance pattern.	I/II	1	7
The presence or absence of 20 harmonics of the cylinder firing rate lines.	I	1	8
Accessory line between CFR 2 and CFR 3.	I	1	9
Accessory line just below CFR 6.	I	1	10
Accessory line between CFR 11 and CFR 12.	I	1	11
Accessory line between CFR 13 and CFR 14.	I	1	12
Accessory line between CFR 16 and CFR 17.	I	1	13
Drive train line below CFR 1.	I	1	14
Drive train line between CFR 1 and CFR 2.	I	1	15
Drive train line between CFR 2 and CFR 3.	I	1	16
Drive train line between CFR 3 and CFR 4.	I	1	17
Drive train line between CFR 4 and CFR 5.	I	1	18

TABLE A-2 (cont.) LEGEND FOR TABLES A-3, A-4, AND A-5

DISCRIMINANT	TYPE CHARACTERISTIC	NUMBER OF ROWS REQUIRED	MATRIX ROWS
Drive train line between CFR 7 and CFR 8.	II	1	19
The amplitude of the drive train line relative to the amplitude of the sixth harmonic of the cylinder firing rate line.	I	1	20
The frequency of the sixth harmonic of the cylinder firing rate line, above or below 135 Hz.	II	1	21
The presence of a chopped drive train line	I	1	22
The frequency ratio of the drive train fundamental to the cylinder firing rate fundamental.	III	4	23-26

TABLE A-3. VEHICLE CHARACTERISTIC MATRIX

Row No.	M-35	ZIL-157	M-113	M-551
1	1.00	1.00	1.00	1.00
2	1.00	1.00	1.00	-1.00
3	-1.00	1.00	1.00	1.00
4	-1.00	-1.00	1.00	-1.00
5	1.00	1.00	-1.00	1.00
6	0.00	1.00	1.00	1.00
7	-1.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	1.00
10	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00
12	1.00	0.00	1.00	0.00
13	1.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00
15	0.00	0.00	1.00	0.00
16	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00
18	0.00	1.00	0.00	0.00
19	-1.00	1.00	-1.00	-1.00
20	0.00	0.00	0.00	1.00
21	-1.00	-1.00	1.00	1.00
22	0.00	1.00	0.00	0.00
23	1.00	-1.00	1.00	1.00
24	1.00	1.00	-1.00	1.00
25	1.00	1.00	-1.00	1.00
26	1.00	1.00	-1.00	-1.00



TABLE A-3. VEHICLE CHARACTERISTIC MATRIX (Cont.)

Row No.	BTR-50				PT-76				M-60				T-55			
1	1.00	1.00	1.00	-1.00	1.00	1.00	1.00	1.00	-1.00	-1.00	1.00	1.00	1.00	1.00	1.00	-1.00
2	-1.00	1.00	1.00	-1.00	1.00	1.00	1.00	1.00	1.00	1.00	-1.00	-1.00	-1.00	-1.00	1.00	1.00
3	-1.00	1.00	1.00	1.00	-1.00	-1.00	-1.00	-1.00	1.00	1.00	-1.00	1.00	1.00	1.00	1.00	1.00
4	1.00	-1.00	1.00	1.00	1.00	1.00	-1.00	-1.00	1.00	1.00	-1.00	1.00	1.00	1.00	1.00	1.00
5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-1.00	1.00	1.00	1.00	1.00	1.00	1.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
8	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
16	1.00	1.00	1.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
23	1.00	1.00	1.00	-1.00	-1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	-1.00	-1.00	-1.00	1.00	1.00	-1.00	-1.00	-1.00	1.00	1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
25	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-1.00	-1.00	1.00	1.00	1.00	1.00	1.00	1.00
26	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLE A-4. WEIGHTED VEHICLE CHARACTERISTIC MATRIX

Row No.	M-35			ZIL-157			M-113			M-551		
	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
1	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
2	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
3	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
4	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	-1.00	-1.00	-1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	1.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00
13	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	-1.00	-1.00	-1.00	1.00	1.00	1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
23	0.25	0.25	0.25	-0.25	-0.25	-0.25	0.25	0.25	0.25	0.25	0.25	0.25
24	0.25	0.25	0.25	0.25	0.25	0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
25	0.25	0.25	0.25	0.25	0.25	0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
26	0.25	0.25	0.25	0.25	0.25	0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25

TABLE A-4. WEIGHTED VEHICLE CHARACTERISTIC MATRIX (Cont.)

Row No.	BTR-50				PT-76				M-60				T-55			
1	0.25	0.25	-0.25	0.25	0.25	0.25	0.25	0.25	-0.25	-0.25	0.25	0.25	0.25	-0.25	-0.25	-0.25
2	-0.25	0.25	-0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	-0.25	-0.25	-0.25	0.25	0.25	0.25
3	-0.25	0.25	0.25	-0.25	-0.25	-0.25	-0.25	-0.25	0.25	0.25	0.25	0.25	0.25	-0.25	0.25	0.25
4	0.25	-0.25	0.25	0.25	0.25	-0.25	-0.25	-0.25	0.25	0.25	-0.25	-0.25	-0.25	0.25	0.25	0.25
5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-1.00	1.00	1.00	1.00	1.00	1.00	1.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
8	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
21	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
23	0.25	0.25	-0.25	-0.25	0.25	0.25	0.25	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	-0.25	-0.25	0.25	0.25	-0.25	-0.25	-0.25	-0.25	0.25	0.25	-0.25	-0.25	0.25	-0.25	-0.25	-0.25
25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	-0.25	-0.25	0.25	0.25	-0.25	-0.25	0.25	0.25
26	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25

TABLE A-5. WEIGHTED AND NORMALIZED VEHICLE CHARACTERISTIC MATRIX

Row No.	M-35			ZIL-157			M-113			M-551		
1	0.10	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.10	0.10
2	0.10	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10	-0.09	-0.10	-0.10
3	-0.10	-0.09	-0.10	0.10	-0.10	0.10	-0.10	0.10	0.10	0.09	0.10	0.10
4	-0.10	-0.09	-0.10	-0.10	-0.10	-0.10	-0.10	0.10	0.10	-0.09	-0.10	-0.10
5	0.39	0.37	0.39	0.39	0.39	0.39	-0.39	-0.39	-0.39	0.37	0.39	0.39
6	0.00	0.00	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.37	0.39	0.39
7	-0.39	-0.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.37	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.39	0.37	0.00	0.00	0.00	0.00	0.39	0.39	0.39	0.00	0.00	0.00
13	0.39	0.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.37	0.00	0.00
15	0.00	0.00	0.00	0.00	0.39	0.39	0.39	0.39	0.00	0.00	0.39	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39
18	0.00	0.00	0.39	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	-0.39	-0.37	0.39	0.39	-0.39	-0.39	-0.39	-0.39	-0.39	-0.37	-0.39	-0.39
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.37	0.39	0.39
21	-0.39	-0.37	-0.39	-0.39	-0.39	-0.39	0.39	0.39	0.39	0.37	0.39	0.39
22	0.00	0.00	0.39	0.39	0.39	0.39	0.00	0.00	0.00	0.00	0.00	0.00
23	0.10	0.09	-0.10	-0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.10	-0.10
24	0.10	0.09	0.10	0.10	-0.10	-0.10	-0.10	-0.10	0.10	0.09	-0.10	-0.10
25	0.10	0.09	0.10	0.10	-0.10	-0.10	-0.10	-0.10	-0.10	0.09	-0.10	0.10
26	0.10	0.09	0.10	0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.09	0.10	-0.10

TABLE A-5. WEIGHTED AND NORMALIZED VEHICLE CHARACTERISTIC MATRIX (Cont.)

Row No.	BTR-50				PT-76				M-60				T-55			
1	0.11	0.11	-0.11	0.11	0.10	0.10	-0.11	-0.09	-0.11	-0.09	0.12	0.12	0.12	-0.12	0.12	-0.12
2	-0.11	0.11	-0.11	0.11	0.10	0.10	0.11	0.09	0.11	0.09	-0.12	-0.12	-0.12	-0.12	-0.12	0.12
3	-0.11	0.11	0.11	-0.11	-0.10	-0.10	-0.11	0.09	0.11	0.09	-0.12	0.12	0.12	0.12	0.12	0.12
4	0.11	-0.11	0.11	0.11	0.10	-0.10	0.11	0.09	0.11	0.09	-0.12	0.12	0.12	-0.12	0.12	0.12
5	0.43	0.43	0.43	0.43	0.39	0.39	0.43	-0.37	0.43	-0.37	0.47	0.47	0.47	0.47	0.47	0.47
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.37	0.00	0.37	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.39	0.39	0.43	0.37	0.43	0.37	0.47	0.47	0.47	0.47	0.47	0.47
8	0.43	0.43	0.43	0.43	0.39	0.39	0.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.37	0.00	0.37	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.43	0.43	0.43	0.43	0.39	0.39	0.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.43	0.00	0.00	0.43	0.37	0.00	0.37	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.43	0.43	0.43	0.43	0.39	0.39	0.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.37	-0.43	-0.37	-0.47	-0.47	-0.47	-0.47	-0.47	-0.47
21	-0.43	-0.43	-0.43	-0.43	-0.39	-0.39	-0.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.37	-0.43	-0.37	-0.47	-0.47	-0.47	-0.47	-0.47	-0.47
23	0.11	0.11	-0.11	-0.11	0.10	0.10	-0.11	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	-0.11	-0.11	0.11	0.11	-0.10	-0.10	0.11	-0.09	0.11	-0.09	0.12	0.12	0.12	0.12	0.12	0.12
25	0.11	0.11	0.11	0.11	0.10	0.10	0.11	0.09	-0.11	0.09	-0.12	-0.12	-0.12	-0.12	-0.12	-0.12
26	-0.11	-0.11	-0.11	-0.11	-0.10	-0.10	-0.11	0.09	0.11	0.09	0.12	0.12	0.12	0.12	0.12	0.12

DO YOU WISH TO DISPLAY THE QUESTIONS? -- Y

1 LIST THE STRONG CFR LINES WITH STRONGEST FIRST:... 3,6.  
 2 STATE PREDOMINANCE PATTERN (0,3,6):..... 0  
 3 WHAT ARE THE FREQUENCIES OF DT1 AND CFR1:..... 18,10  
 4 TRANSMISSION TYPE MANUAL-M, AUTOMATIC-A, UNKNOWN-U A  
 5 IS THERE A STRONG DRIVE TRAIN LINE PRESENT?..... Y  
 6 ARE ALL CFR LINES PRESENT TO CFR20?..... N  
 7A ACCESSORY LINES BETWEEN CFR 2 & 3?..... N  
 7B ACCESSORY LINES BETWEEN CFR 5 & 6?..... N  
 7C ACCESSORY LINES BETWEEN CFR 11 & 12?..... N  
 7D ACCESSORY LINES BETWEEN CFR 13 & 14?..... Y  
 7E ACCESSORY LINES BETWEEN CFR 16 & 17?..... N  
 8A DRIVE TRAIN LINES BETWEEN CFR 0 & 1?..... N  
 8B DRIVE TRAIN LINES BETWEEN CFR 1 & 2?..... Y  
 8C DRIVE TRAIN LINES BETWEEN CFR 2 & 3?..... N  
 8D DRIVE TRAIN LINES BETWEEN CFR 3 & 4?..... N  
 8E DRIVE TRAIN LINES BETWEEN CFR 4 & 5?..... N  
 8F DRIVE TRAIN LINES BETWEEN CFR 7 & 8?..... N  
 9 IS THE AMPLITUDE OF DT  $\geq$  CFR6?..... N  
 10 IS CFR6  $>$  135 HZ?..... Y  
 11 IS THE DT LINE CHOPPED AND NOT CFR COINCIDENT?.... N

VER.: 113, RANK = 1.000

Note: Y = Yes

N = No

CONTINUE? -- Y

FIGURE A-1. SAMPLE OUTPUT FROM INTERACTIVE CLASSIFICATION PROGRAM

```

DIMENSION W(26),ID(24),MID(24),X(26),A(26,24),Q(22,12),
1 Y(26),XL(2),FMT(4),FMTA(4),ANSW(20)
DATA FMT,FMTA/'(1X,A3,10A5,2X,S) ','(1X,A3,3H-- ,S) '/,
1 YES, AUTO, UNK /'Y', 'A', 'U'/
C: READ IN DATA BASE
TYPE 600
ACCEPT 500, NAME
CALL IFILE(8,NAME,' ')
READ (8,521) NVEH,NDCCR,NCOL,NQ,LQ
READ (8,501) (ID(I),I=1,NCOL)
READ (8,502) (W(I), I=1,NDCCR)
READ (8,503) ((A(I,J), J=1,NCOL), I=1,NDCCR)
READ (8,504) ((Q(I,J),J=1,LQ),I=1,NQ)
REWIND 8
TYPE 525
ACCEPT 710, ANS
IF(ANS .EQ. YES) GO TO 21
LQ=1
DO 20 K=1,4
20 FMT(K)=FMTA(K)
C: WEIGHT AND NORMALIZE TEST MATRIX
21 DO 3 J=1,NCOL
SUM=0.0
DO 2 I=1,NDCCR
A(I,J)=A(I,J)*W(I)
2 SUM=SUM+A(I,J)*A(I,J)
SUM=1.0/(SUM**0.5)
DO 3 I=1,NDCCR
3 A(I,J)=A(I,J)*SUM
C: INITIALIZE 'UNKNOWN'
8888 DO 4 I=1,NDCCR
4 X(I)=1.
C: CLASSIFICATION QUESTIONS
TYPE FMT, (Q(1,J), J=1,LQ)
ACCEPT 721, XL(1), XL(2)
R=XL(1)/XL(2)
TYPE FMT, (Q(2,J), J=1,LQ)
ACCEPT 720, IPD
TYPE FMT, (Q(3,J), J=1,LQ)
ACCEPT 721, XL(1), XL(2)
D=XL(1)/XL(2)
DO 930 K=4,20
TYPE FMT, (Q(K,J), J=1,LQ)
930 ACCEPT 710, ANSW(K-3)

```

FIGURE A-2. LISTING OF INTERACTIVE CLASSIFICATION PROGRAM

```

C: WEIGHT AND NORMALIZE 'UNKNOWN'
    SUM=0.0
    DØ 400 I=1,NDCR
    X(I)=X(I)*W(I)
400    SUM=SUM+X(I)*X(I)
    SUM=1.0/(SUM**0.5)
    DØ 401 I=1,NDCR
401    X(I)=X(I)*SUM
C: CALCULATE Y(J)
    DØ 415 J=1,NCØL
    MID(J)=ID(J)
    SUM=0.0
    DØ 410 I=1,NDCR
410    SUM=A(I,J)*X(I)+SUM
415    Y(J)=SUM
C: SORT Y(J)
    DØ 420 J=1,NCØL-1
    DØ 420 K=J+1,NCØL
    IF(Y(J) .GE. Y(K)) GØ TØ 420
    YA=Y(J)
    Y(J)=Y(K)
    Y(K)=YA
    KID=MID(J)
    MID(J)=MID(K)
    MID(K)=KID
420    CONTINUE
C: ØUTPUT
    K=1
40    TYPE 697, MID(K), Y(K)
    IF(Y(K) .NE. Y(K+1)) GØ TØ 30
    K=K+1
    GØ TØ 40
C: CONTINUE ØR TERMINATE
30    TYPE 698
    ACCEPT 710, ANS
    IF(ANS .EQ. YES) GØ TØ 8888
    CALL EXIT
C: FØRMAT SECTION
500    FØRMAT(A5)
501    FØRMAT(12I4)
502    FØRMAT(13F4.0)
503    FØRMAT(12F4.0)
504    FØRMAT(A~,10A5)
521    FØRMAT(5I4)
525    FØRMAT(' DØ YØU WISH TØ DISPLAY THE QUESTIONS? -- ',S)
600    FØRMAT(' WHERE ARE THE DATA? -- ',S)
697    FØRMAT('/', VEH.: 'I4, ', RANK = 'F6.3)
698    FØRMAT('///' CONTINUE? -- ',S)
700    FØRMAT(F)
710    FØRMAT(A1)
720    FØRMAT(I)
721    FØRMAT(2F)
    END

```

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FIGURE A-2 (Cont.) LISTING OF INTERACTIVE  
CLASSIFICATION PROGRAM



## C: CONSTRUCT 'UNKNOWN' VECTOR

```

      IF( R .GT. 1.40) X(1)=-1.
      IF( R .GE. 0.70 .AND. R .LT. 1.75) X(2)=-1.
      IF( R .GE. 0.45 .AND. R .LT. 1.00) X(3)=-1.
      IF((R .GE. 0.36 .AND. R .LT. 0.58) .OR.
      1 ( R .GE. 0.77 .AND. R .LT. 1.27)) X(4)=-1.
      IF(ANSW(1) .EQ. AUT0) X(5)=-1.
      IF(ANSW(1) .EQ. UNK) X(5)=0.
      IF(ANSW(2) .NE. YES) X(6)=0.
      IF(IPD .EQ. 0) X(7)=0.
      IF(IPD .EQ. 6) X(7)=-1.
      D0 934 K=3,13
      IF(ANSW(K) .NE. YES) X(K+5)=0.
934  CONTINUE
      IF(ANSW(14) .NE. YES) X(19)=-1.
      IF(ANSW(15) .NE. YES) X(20)=0.
      IF(ANSW(16) .NE. YES) X(21)=-1.
      IF(ANSW(17) .NE. YES) X(22)=0.
      IF( D .GE. 2.90) X(23)=-1.
      IF( D .GE. 1.45 .AND. D .LT. 3.60) X(24)=-1.
      IF( D .GE. 0.90 .AND. D .LT. 2.20) X(25)=-1.
      IF((D .GE. 0.40 .AND. D .LT. 1.20) .OR.
      1 ( D .GE. 1.60 .AND. D .LT. 2.60) .OR.
      2 ( D .GE. 3.10 .AND. D .LT. 4.10)) X(26)=-1.

```

FIGURE A-2 (Cont.) LISTING OF INTERACTIVE CLASSIFICATION PROGRAM

[illegible]

FIGURE A-3. LISTING OF INPUT FILE FOR INTERACTIVE CLASSIFICATION PROGRAM

-1	-1	1	1	-1	-1	-1	-1	-1	-1	-1	-1
1	1	1	1	1	1	-1	-1	-1	-1	-1	-1
0	0	0	0	0	0	0	0	0	0	1	1
0	0	0	0	0	0	0	0	0	0	0	0
-1	-1	-1	-1	-1	-1	1	1	1	1	1	1
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
0	0	1	1	1	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
1	1	-1	-1	1	1	1	1	1	1	1	-1
1	1	-1	-1	1	1	1	-1	1	1	-1	-1
1	1	1	1	-1	-1	-1	-1	1	1	-1	-1
-1	-1	1	1	-1	-1	1	-1	-1	-1	-1	-1
1	1	1	1	-1	-1	-1	-1	-1	1	-1	1
1	1	1	1	1	1	-1	1	1	1	1	1
1	1	1	1	-1	-1	-1	-1	-1	-1	1	-1
-1	-1	-1	-1	-1	-1	1	1	1	1	1	1

- 1 LIST THE STRONG CFR LINES WITH STRONGEST FIRST:...
- 2 STATE PREDOMINANCE PATTERN (0,3,6):.....
- 3 WHAT ARE THE FREQUENCIES OF DT1 AND CFR1:.....
- 4 TRANSMISSION TYPE MANUAL-M, AUTOMATIC-A, UNKNOWN-U
- 5 IS THERE A STRONG DRIVE TRAIN LINE PRESENT?.....
- 6 ARE ALL CFR LINES PRESENT TO CRF20?.....
- 7A ACCESSORY LINES BETWEEN CFR 2 & 3?.....
- 7B ACCESSORY LINES BETWEEN CFR 5 & 6?.....
- 7C ACCESSORY LINES BETWEEN CFR 11 & 12?.....
- 7D ACCESSORY LINES BETWEEN CFR 13 & 14?.....
- 7E ACCESSORY LINES BETWEEN CFR 16 & 17?.....
- 8A DRIVE TRAIN LINES BETWEEN CFR 0 & 1?.....
- 8B DRIVE TRAIN LINES BETWEEN CFR 1 & 2?.....
- 8C DRIVE TRAIN LINES BETWEEN CFR 2 & 3?.....
- 8D DRIVE TRAIN LINES BETWEEN CFR 3 & 4?.....
- 8E DRIVE TRAIN LINES BETWEEN CFR 4 & 5?.....
- 8F DRIVE TRAIN LINES BETWEEN CFR 7 & 8?.....
- 9 IS THE AMPLITUDE OF DT >= CFR6?.....
- 10 IS CFR6 > 135 HZ?.....
- 11 IS THE DT LINE CHOPPED AND NOT CFR COINCIDENT?....

FIGURE A-3. (Cont.) LISTING OF INPUT FILE FOR INTER-  
ACTIVE CLASSIFICATION PROGRAM

## FIGURE A-4

CONSTRUCTION OF INPUT FILE FOR INTERACTIVE  
VEHICLE CLASSIFICATION

<u>Record 1</u>	Format: 5I4
Variable	Definition
1	Number of Vehicles in Data Base
2	Number of Rows in Vehicle Characteristic Matrix (Matrix A)
3	Number of Columns in Vehicle Characteristic Matrix (Matrix A)
4	Number of Questions for conversational input of Characteristics of Vehicle to be Identified
5	Length of questions, in words (5 characters per word)
<u>Record 2-3</u>	Format: 12I4 (Each record) Identification numbers used to label each column of the Vehicle Characteristic Matrix (Matrix A)
<u>Records 4-5</u>	Format: 13F4.0 (each record) The combined weights (s. w.) for each row of the Vehicle Characteristic Matrix (Matrix A)
<u>Records 6-57</u>	Format: 12I4 (each record) Vehicle Characteristic Matrix, Two records per row. (Matrix columns 1 to 12 are in the first record, and columns 13 to 24 in the second.)
<u>Records 58-77</u>	Format: A3,10A5 (each record) List of Questions for conversational input of characteristics of vehicle to be identified. First three characters are the question identifiers, the remaining 50 characters form the question text.

APPENDIX D

Excerpts from Line Tracking Directional System (LITRADS)  
NADC APS-2, 6 Feb. 1970, TM020670, Unclassified

The NADC is developing a direction finding (DF) system. The major components of this system are:

1. In-buoy bearing computer
2. Phase lock loop for target location and identification
3. Digital constant band width tracking filter
4. CARDONUT microphones for A/C rejection

1. Two basic bearing computation techniques are being considered: one similar to the DIFAR technique, the other to the DARAS technique of direction finding. The bearing computations will be converted to a digital message for transmission when the transmitter is enabled by the phase lock loop.

2. Sufficient literature has been written on the DIFAR, DARAS and line spectrum detector with phase lock loop (Figures 1, 2 and 3), and only certain aspects of the phase lock loop (P.L.L.) will be iterated.

3. The voltage controlled oscillator (V.C.O.) of the P.L.L., through proper design, is made to sweep through a band of frequencies until it locates a spectral line equal in frequency and phase to that of the V.C.O. The system will then stop sweeping and lock onto this line. The signal is then classified through identification logic as being a target of interest or some other acoustic generator. The predetection filter of the present PLL passes all the frequencies over which the VCO searches. In order to prevent noise or spectral lines from unwanted generators from masking the target signal and

forcing the system to unlock, a narrow band predetection filter is being implemented. The center frequency of this digital bandpass filter will track the frequency ( $f_0$ ) of the VCO as it sweeps or locks onto a line. In addition, this filter maintains a constant bandwidth centered at  $f_0$ . Therefore the digital predetection tracking filter will present to the PLL system a narrow band passed input signal centered at  $f_0$ .

4. This method of filter design and one PLL can be used to control several tracking filters simultaneously with each filter of equal or different bandwidths.

5. Figure 4 is a block diagram of a tracking filter system. It is noted that four filters are being controlled by one PLL and that the input pass bands of the directional system are different from that of the PLL.

A self-starting, self-correcting ring counter is formed by combination of J & K Flip Flops and NAND gates. This counter drives the sequential switch through the bandpass filter control, setting the filters' bandwidth and response curve. The VCO is used as a clock for the ring counter and the filter tracks its center frequency with the clock while keeping its bandwidth constant.

6. A CARDONUT microphone array will be used for this system. This microphone will attenuate signals arriving from the hemisphere above the buoy, specifically A/C, but has no effect on the signals from the sides of the buoy. This enhances system performance in three ways:

(a) The PLL will not waste time locking on A/C line spectra thus improving the probability of detecting trucks.

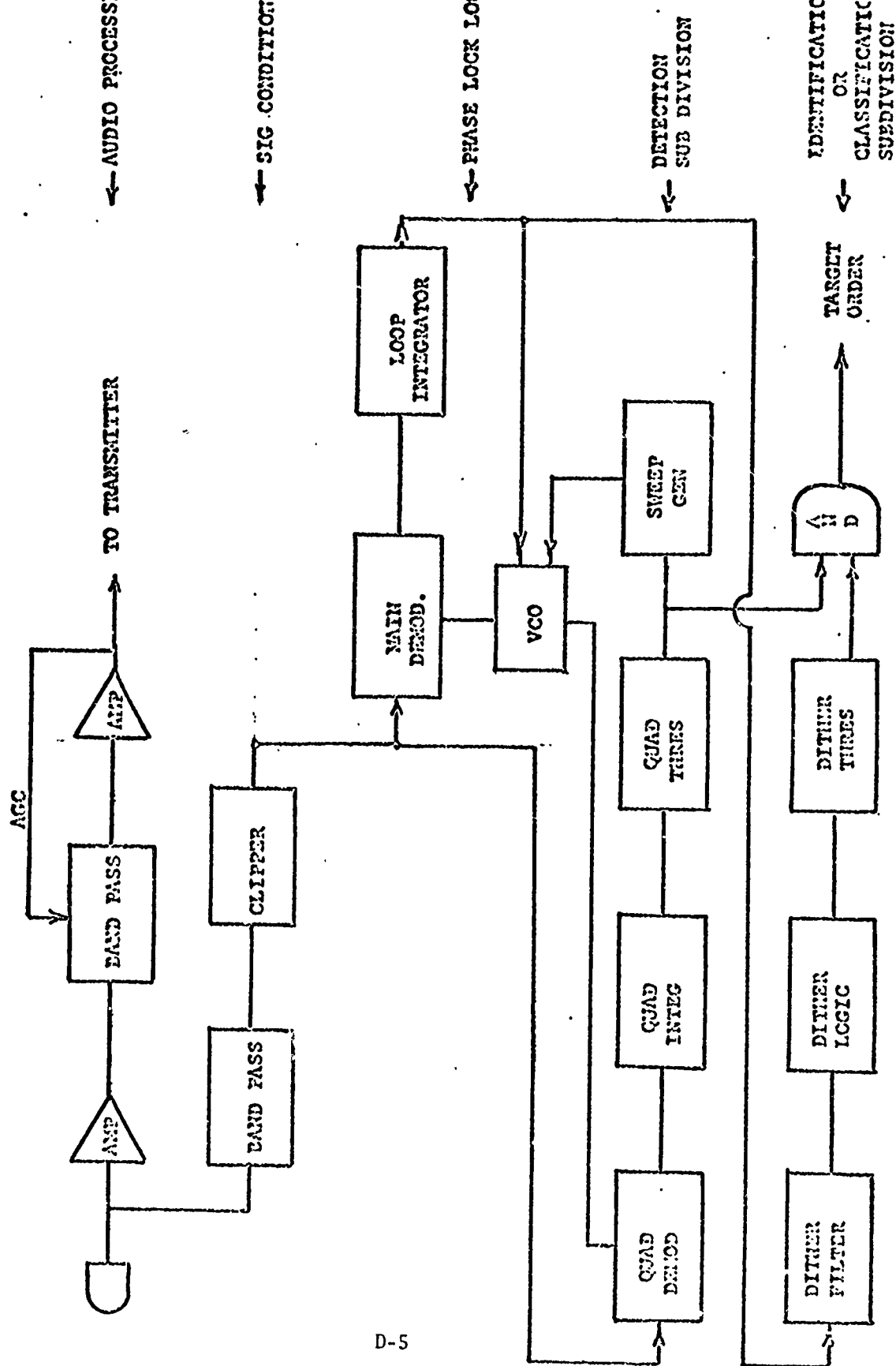
(b) When A/C and trucks are both in the area, the CARDONUT will prevent the A/C signal from masking the truck.

(c) Directional bearings will be computed primarily on truck signals and not be smeared by acoustic energy radiated by A/C.

7. Figure 5 is a block diagram of a direction finding system that uses the techniques described above. The phase lock loop with a tracking filter searches until a spectral line is located. A detection of a line enables the directional processor and a bearing is calculated, stored, and continuously updated. Identification or classification logic in the PLL system analyzes the signature of the detected line and determines if it is a target of interest (truck) or some other acoustic generator. If not a truck, the system unlocks and begins to search. If a truck is identified, the unit transmitter is turned on to transmit a buoy identification and a bearing to the target. This message will repeat with updated bearing as long as the target is detected and identified by the PLL.



# LINE SPECTRUM DETECTOR SYSTEM



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FIGURE 1

# DIFAR TYPE SYSTEM BLOCK DIAGRAM

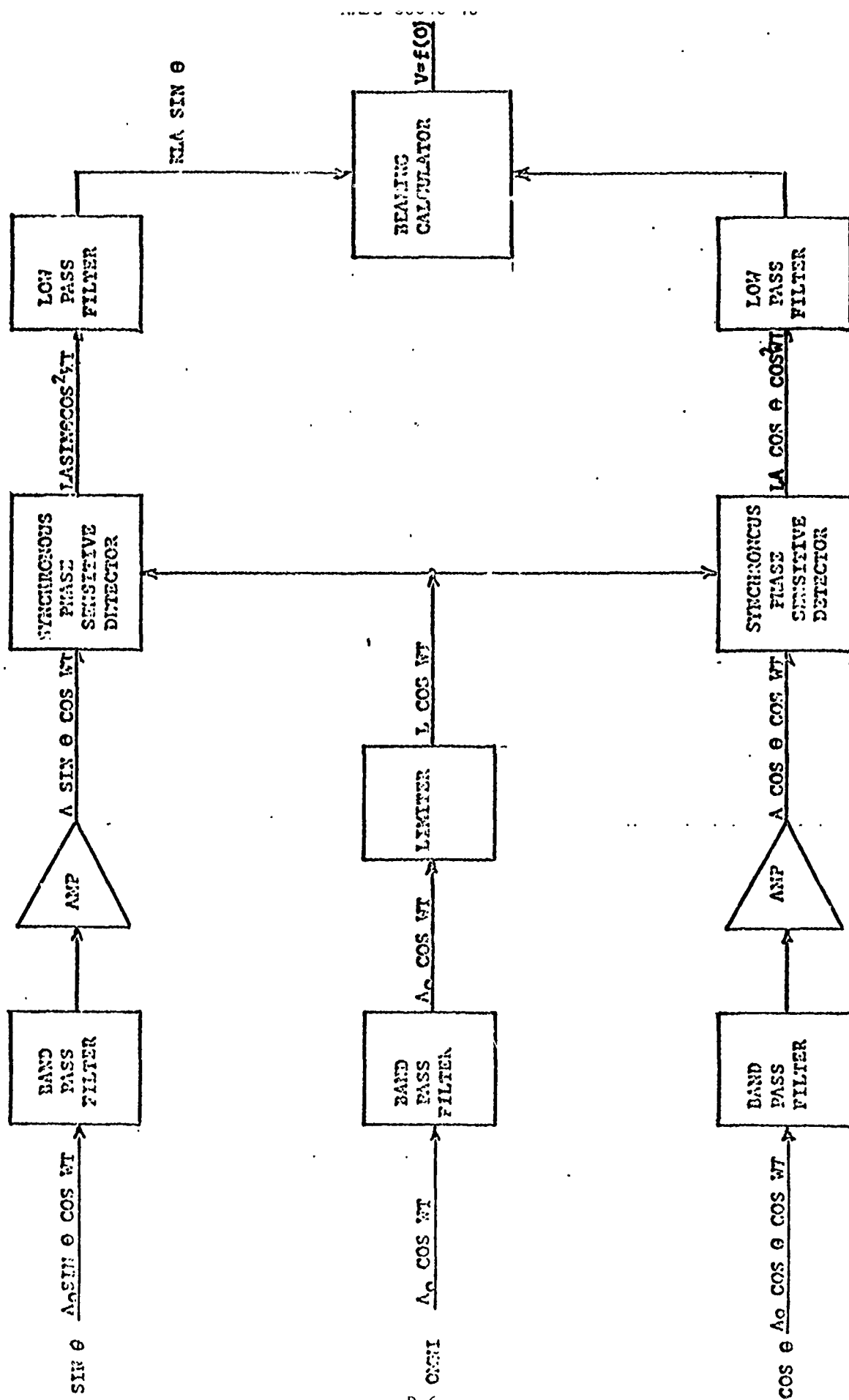
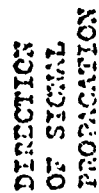


FIGURE 2



**FIGURE 3**

## DIGITAL TRACKING FILTER

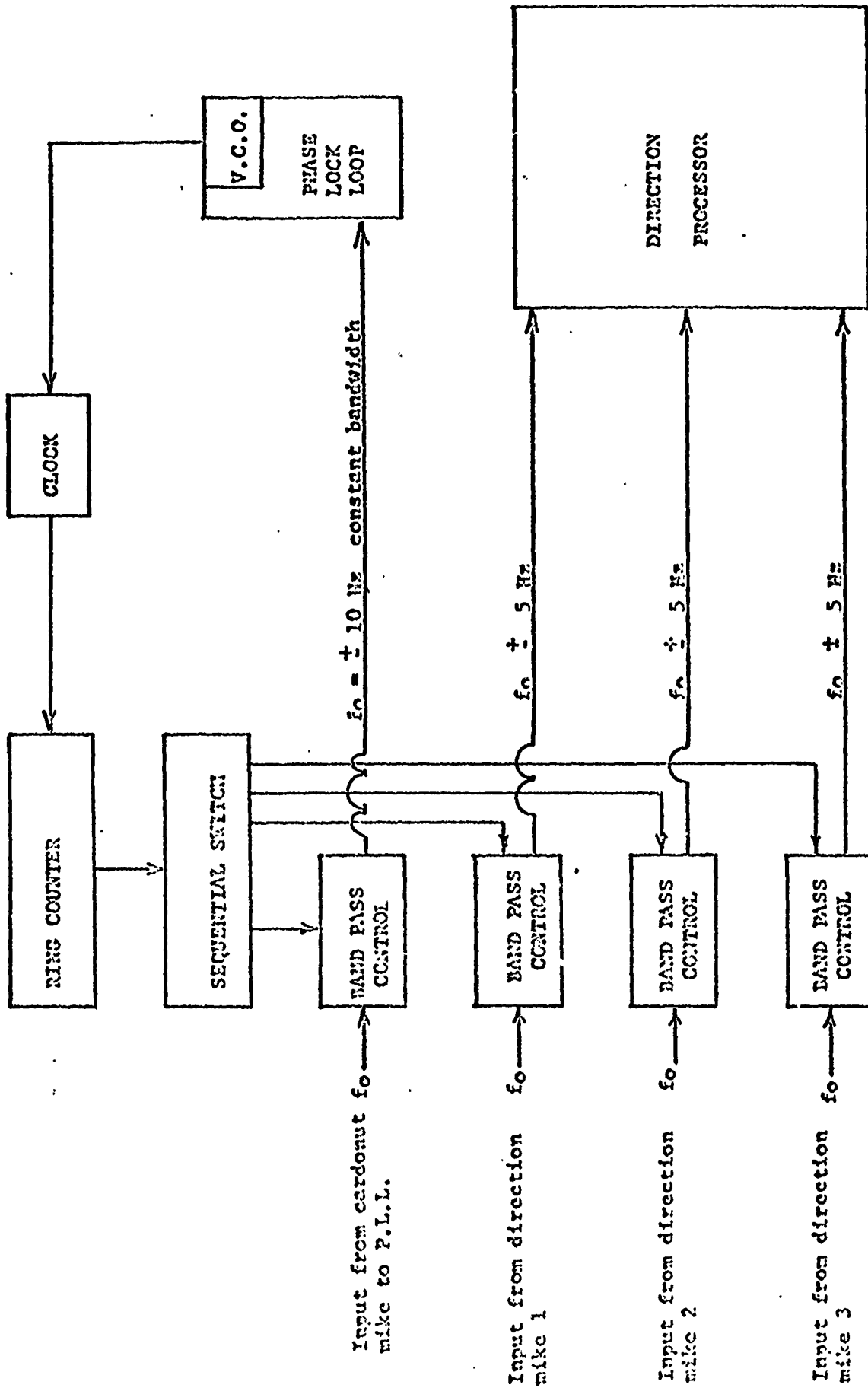
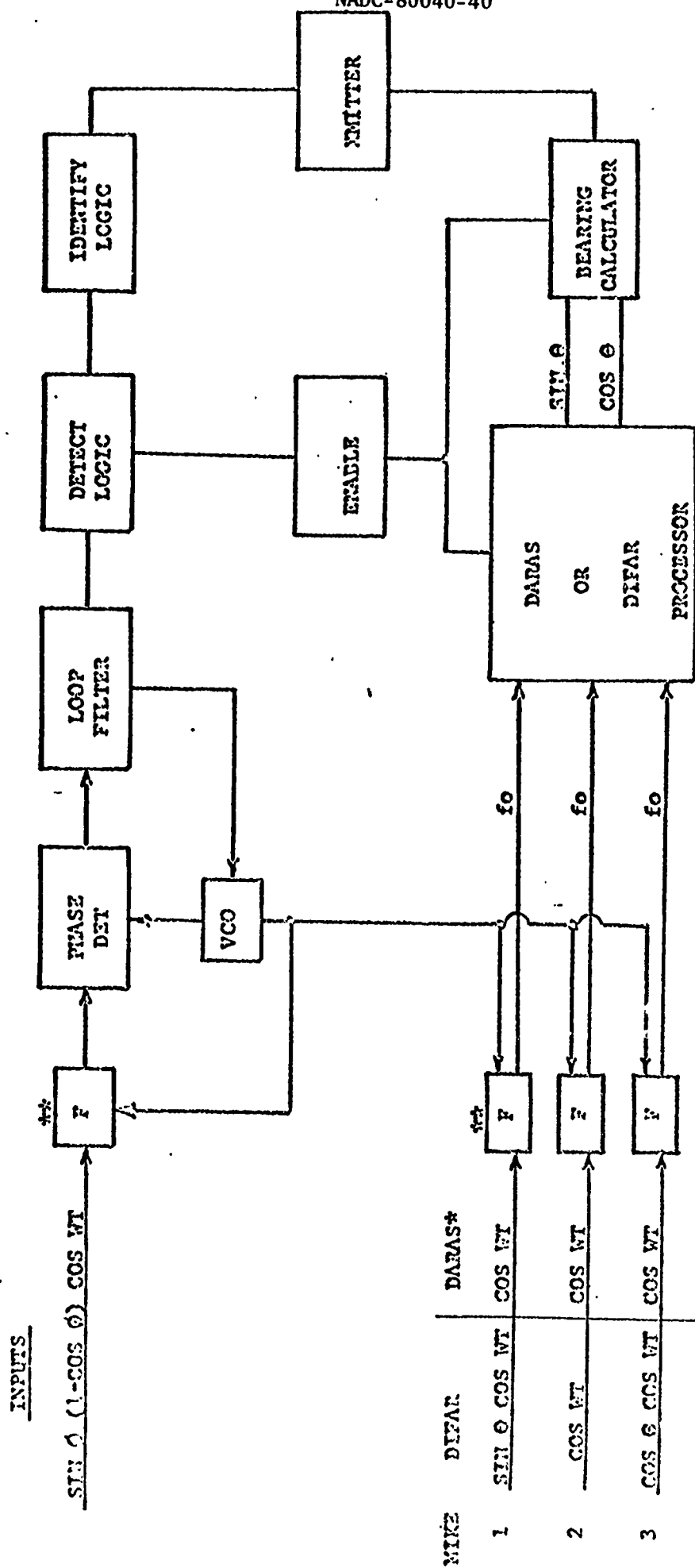


FIGURE 4

# DIRECTIONAL SYSTEM USING TRACKING FILTER



\* DARAS SENSING ELEMENTS ARE THREE ORTHOGONALLY ORIENTED OMNIDIRECTIONAL MICROPHONES.

\*\* F = NARROW BAND CONSTANT BANDWIDTH TRACKING FILTERS.

FIGURE 5

APPENDIX E

Excerpts from An Experiment in Direction Finding  
and Directional Aspects of Vehicle Detection,  
NADC APS-2, 16 Feb. 1970, TM021670, Unclassified

**PURPOSE:** The purpose of this experiment was to demonstrate the feasibility of utilizing direction finding as a means of improving detection and classification performance of acoustic vehicle detectors and to explore the possibility of using bearing information to accomplish functions such as tracking and determining closest point of approach (CPA). It was also desired to make some estimate of measurement accuracies for bearing computations.

**TEST LOCATION AND EQUIPMENT:** The experiment was conducted at the Naval Air Development Center. Figure (1) is a diagram of the test site showing the location of the test buoy with respect to important physical surroundings. Figure (1) also shows directions with respect to true north and it is annotated with vehicle movement with respect to the buoy. The buoy was located approximately 100 meters from the road and was physically oriented such that the proper axis of the buoy pointed toward true north. The vehicle utilized was a 1½ ton panel truck. The detecting buoy consisted of two CBS bigradient microphones and an omni microphone whose outputs were connected to a standard DIFAR multiplexer (see Figure (2) for microphone polar response curves). An RF link was provided to transmit data back to an AQA-7 spectrum analyzer and bearing calculator.

**CONDUCT OF TESTS:** The experiment was divided into three different tests. In the first test the truck was moved to selected bearings and allowed to idle motionless while the AQA-7 spectrum analyzed the acoustic signal from the vehicle and calculated bearings on spectral components. At the test site, bearings from the buoy to the vehicle were established with a compass rose and eyepiece. These bearings were communicated to the processor area where they could be annotated and compared to bearings calculated by the AQA-7.

The second test consisted of a radial run past the buoy from northeast to southwest ( $10^{\circ}$  to  $310^{\circ}$ ). For this and the succeeding part of the experiment a loud speaker was mounted on the truck and a single tone frequency at 161 Hz was broadcast in the direction of the buoy. This was done because the AQA-7 is not equipped to track a vehicle type line and the condition of the terrain was such that constant changes in rpm were necessary. The vehicle speed was maintained between 3 to 5 mph and bearing and time checks were transmitted back for annotation to the AQA-7 bearing track.

The final test was an approximately circular run at 3 to 5 mph. The terrain over which the vehicle passed included the road but was mostly overland and, as seen in Figure (1), traversed a hilly area southwest of the buoy roughly between  $150^{\circ}$  and  $200^{\circ}$  relative to true

north. The radius of the circle was approximately 175 meters.

**SOURCES OF ERROR:** Some of the main sources of error are:

1. All bearing reports from the site which are used for comparison purpose were made by eyeball estimates and were reported to the nearest  $5^{\circ}$ .
2. The DIFAR buoy induced error due to multiplexing and is estimated at  $\pm 2.5^{\circ}$ .
3. Processor induced error is estimated at  $\pm 2.5^{\circ}$  on the average.
4. A windscreen was utilized which is known to affect a phase mismatch between the omni and bigradient test microphones. The error induced here is not estimated. The microphones were borrowed from CBS laboratories and complete matching to the DIFAR buoy was not attempted prior to the test.
5. Large errors were induced by the terrain. A high hill which commanded the better part of two quadrants produced reflections and induced multipath errors into the bearing estimate at the processor.
6. The processor was designed for submerien detection and requires long integration time and reasonably steady spectral lines to calculate bearings.

**RESULTS:** Figure (3) is the AQA-7 paper record obtained during the first test. The bearings transmitted by voice during the test are annotated in the third column next to readings which were obtained from the AQA-7 numerical readout at the same time. Column 1 is a LOFARGRAM of the spectrum analyzer data. In addition, bearing tracks of short term (continuous marks) and long term integrated data (spaced marks) can be seen on both the LOFARGRAM column and the center columns. As can be seen from the figure, bearings calculated by the AQA-7 are in good agreement with actual bearings in the first and fourth quadrants. Multipath errors in the second and third quadrants produce some fairly large differences. With some exceptions the bearing tracks show that consistent results can be obtained even on short term integrated data. Bearing tracks can be expected to vary widely if the line is unstable as can be seen on the LOFARGRAM of those tracks which appear scattered.

Figure (4) is the record of the results for test #2, the radial run, and test #3, the circular run. The 161 Hz line on which bearings are being calculated by the AQA-7 is shown in the LOFARGRAM of channel 1. Observe the very sharp change in bearing as the truck passes CPA and the



bearing rate becomes maximum. As can be seen from Figure (1) CPA occurs at approximately  $340^{\circ}$  and this is also approximately where the bearing rate reaches its maximum value on the record. After the radial run, the vehicle was stopped for some time near  $310^{\circ}$  and a very good track was obtained on the line which steadily pin pointed the vehicle within  $10^{\circ}$ .

The bearings circled in the third column are the best estimates of vehicle position vs time which could be made at the site. The continuous plot is the bearing track supplied by the AQA-7 on the short term integrated data. The heavier dots just below the short term track is the bearing track based on a longer integration period. As can be seen from the record, a very accurate track of the vehicles progress was obtained with the associated calculated long term bearing lagging the actual position of the truck by about 60 to 80 seconds.

**CONCLUSIONS:** The results of even this crude test show that accurate estimates of truck bearings may be obtained. The bearing line indicates a moving or stationary truck and the bearing rate of change provides a good estimate of CPA. Multiple tracks could quite easily provide enough information to establish the number of trucks in a convoy. The technique used in this experiment will be combined with the method described in TM020670, LITRADS, to provide accurate line tracking and in-buoy bearing computation.

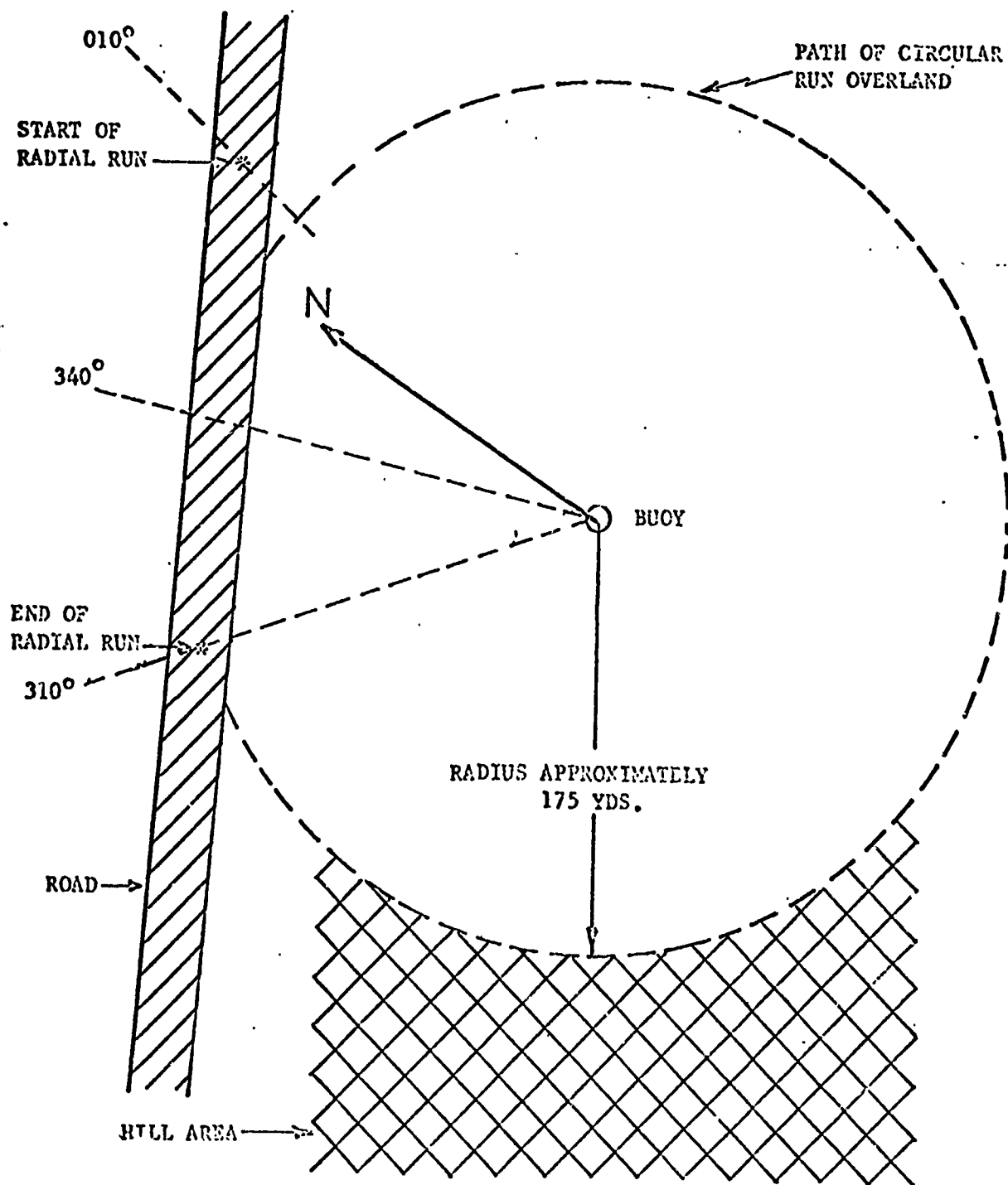


FIGURE I  
E-5

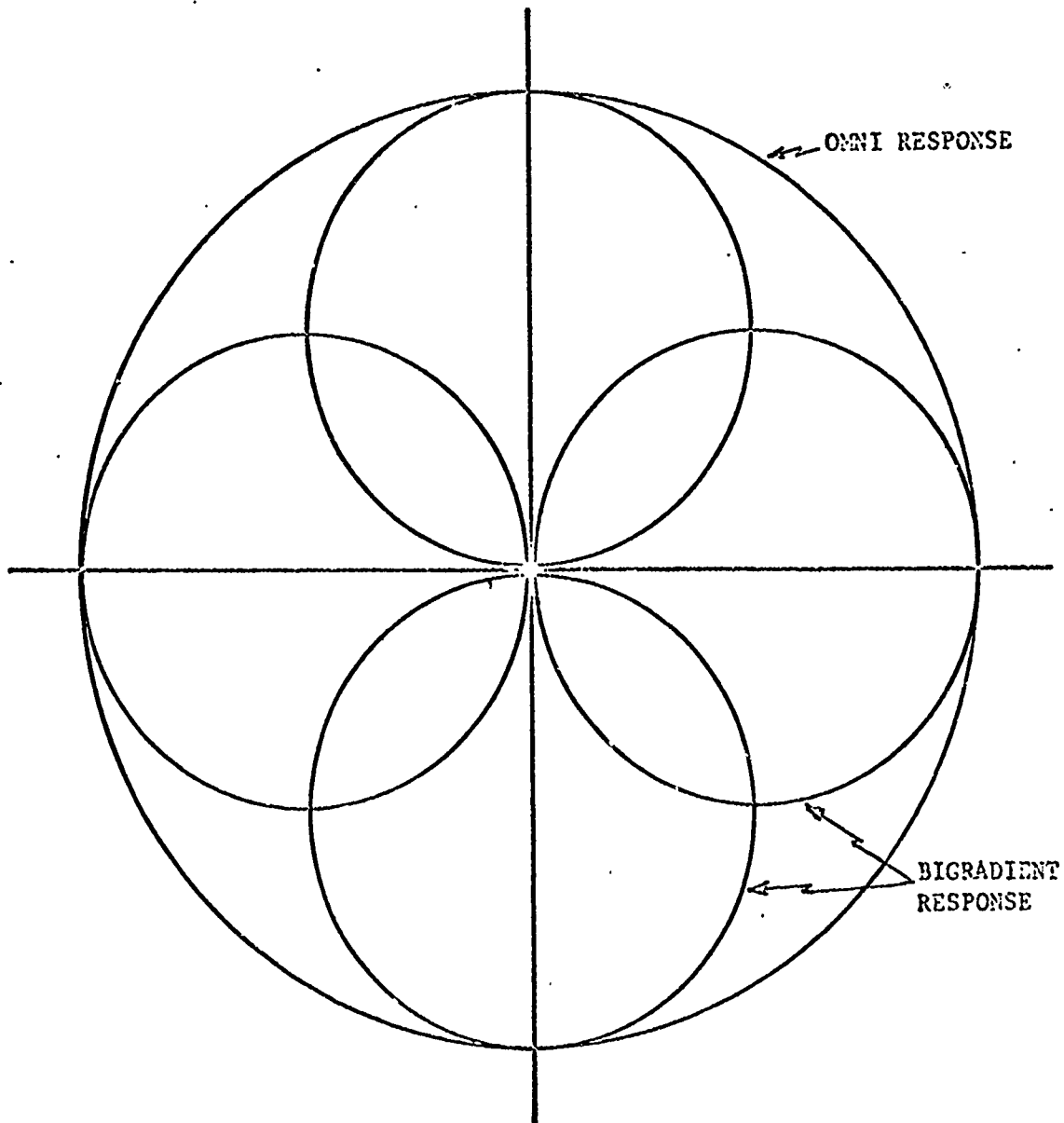
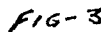
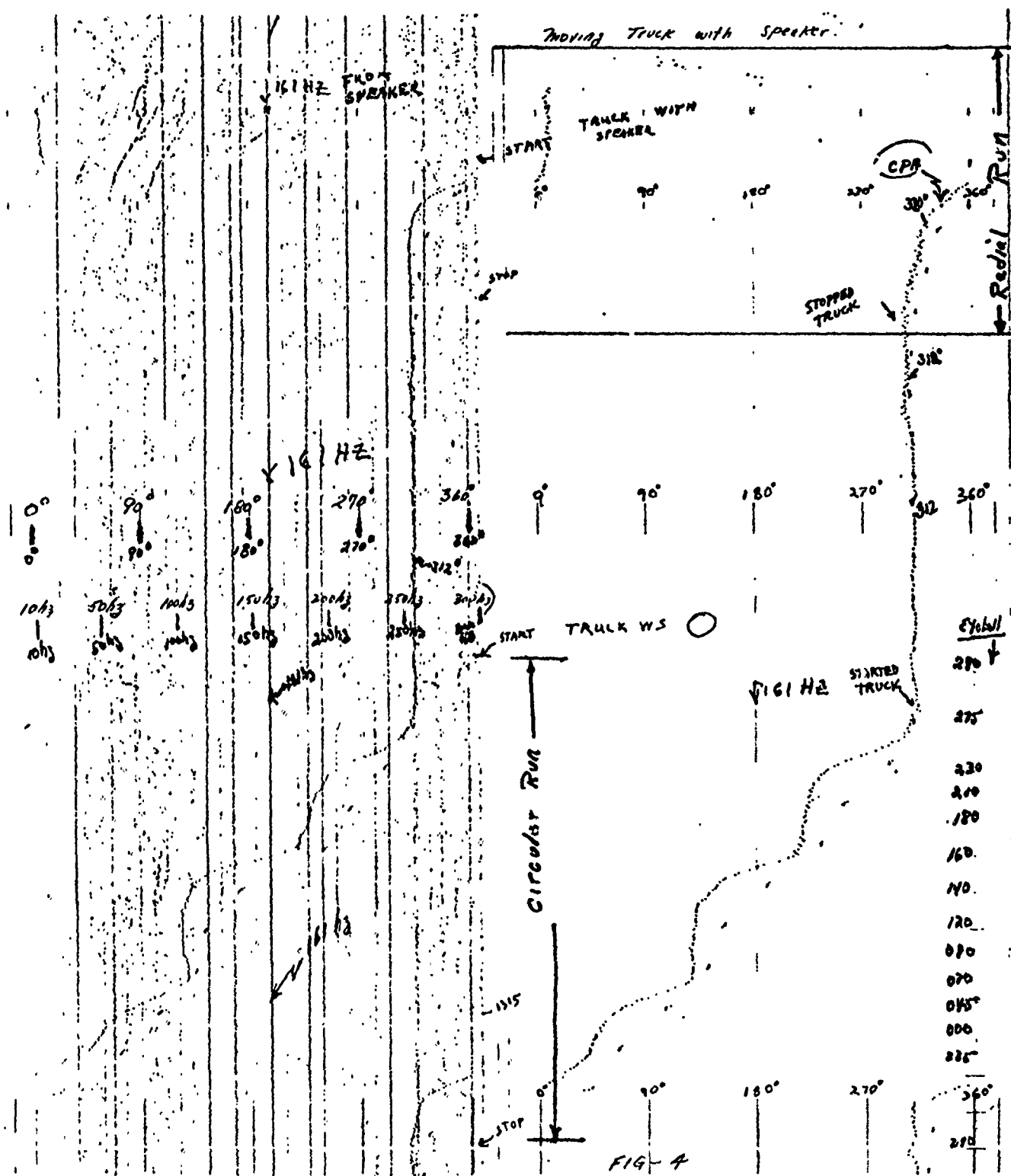


FIGURE 2





APPENDIX F

Excerpts from Linear Arrays

NADC APS-2, 28 Jan. 1970, TM012870, Unclassified

LINEAR ARRAYS

Consider a linear array of equally spaced elements; assume a plane wave arrival whose wave front is at some angle  $\theta$  with respect to the axis of the array. The output of the  $M^{\text{th}}$  element relative to that of the zeroth element will be delayed by the amount of time necessary for sound to travel the distance

$$d_M = MS \sin \theta$$

The corresponding phase delay for sound of frequency  $W = 2\pi f$  and wave length  $\lambda$  is

$$u_M = \frac{2\pi d_M}{\lambda} = Mu$$

$$\text{Where } u = \frac{2\pi S}{\lambda} \sin \theta$$

The output voltage of the  $M^{\text{th}}$  element of voltage response  $v_m$  will be

$$V_m = v_m \cos (Wt + (M-1)u)$$

The array voltage will just be the sum of these terms from each element

$$V = v_0 + v_1 + v_2 + \dots + v_m$$

$$V = v_0 \cos wt + v_1 \cos (wt + u) + v_2 \cos (wt + 2u) + v_3 \cos (wt + 3u) + \dots + v_m \cos (wt + (M-1)u)$$

In complex notation

$$V = (v_0 + v_1 e^{iu} + v_2 e^{i2u} + v_3 e^{i3u} + \dots + v_m e^{i(M-1)u}) e^{iwt}$$

Assume the matching of response for all elements

$$\text{i.e., } v_0 = v_1 = v_2 \dots = 1$$

$$v = (1 + e^{iu} + e^{2iu} + e^{3iu} + \dots + e^{(M-1)iu}) e^{iwt} \quad (1)$$

$$e^{iu} v = (e^{iu} + e^{2iu} + e^{3iu} + \dots + e^{Miu}) e^{iwt} \quad (2)$$

Subtracting equation (1) from equation (2) yields

$$e^{iu} v - v = (e^{Miu} - 1) e^{iwt}$$

$$v = \frac{(e^{Miu} - 1) e^{iwt}}{(e^{iu} - 1)}$$

Neglecting time dependence and manipulating yields

$$v = \frac{\sin(Mu/2)}{\sin(u/2)}$$

Now  $b(\theta)$ , the beam pattern, is the square of the voltage "pattern"

normalized to unity at  $\theta = 0^\circ$

$$\therefore b(\theta) = \left( \frac{v}{M} \right)^2 = \left[ \frac{\sin \frac{M\pi S \sin \theta}{\lambda}}{M \sin \frac{\pi S \sin \theta}{\lambda}} \right]^2$$

If the spacing between elements is  $\frac{\lambda}{2}$ , the beam pattern

reduces to:

$$b(\theta) = \left[ \frac{\sin \left( \frac{M\pi \sin \theta}{2} \right)}{M \sin \left( \frac{\pi \sin \theta}{2} \right)} \right]^2$$



The sensitivity of the minor lobe and the location of nulls in the pattern  $\left[ \text{where } \sin \left( \frac{M\pi S \sin \theta}{\lambda} \right) = 0 \right]$  can be altered by either or both non-uniform spacing, and/or "shading" (amplitude weighting specific elements) techniques. The effect of non-uniform spacing is to narrow the major lobe (widen the lobes of minimum or low sensitivity) and, unfortunately, narrow the bandwidth over which the array can be used for beamforming purposes. The effects of shading are the lowering of the side lobe levels (decrease the sensitivity of the minor lobes below that of an unshaded array) and the widening of the major lobe (less angles of low sensitivity than an unshaded array).

Neither of the undesired effects of non-uniform spacing nor shading can be tolerated in the rejection of aircraft noise from an Acoubuoy. The desired effect is a large sound rejection (50 to 70 db) (very low sensitivity) at angles near  $\theta = 90^\circ$ , gradually diminishing to a differentiable sound rejection at  $\theta = 10^\circ$  (3 to 5 db). This type of specification is unattainable with an unshaded uniformly spaced  $\left( \frac{\lambda}{2} \right)$  linear array of any reasonable length. A maximum minor lobe level of -50 db at about  $90^\circ$  for  $\frac{\lambda}{2}$  spacing would require about 335 elements in an array of  $167 \lambda$  long. If the frequency of interest is between 30 and 120 Hz, the length of the array necessary would be about 3000 ft. This length requirement may be reduced somewhat by non-uniform spacing but the band of interest would have to be narrowed to less than one octave. Shading techniques could be applied to meet the required rejection specification at about  $\theta = 90^\circ$ .

but at the possible sacrifice of losing rejection capability at the small angles. It appears, from the enormously large rejection requirement over such a large angular span, that an additive linear array of omnidirectional elements for use in aircraft noise rejection is unfeasible.

Multiplicative arrays are different from linear additive arrays in that the output of each element is not added to get the array voltage output but is multiplied by either another element output or the product of other element outputs or weighting functions and other weighting element outputs. The effect of multiplicative arrays is to narrow the major lobe but this requires high S/N ratios and uncorrelated noise which is not the case under consideration. Even if the narrowed major lobe of a multiplicative array were satisfactory, the length of the array would still be prohibitive.

APPENDIX G

Excerpts from Directional Survey  
Techniques and Implementation, NADC APS-2,  
3 Feb. 1970, TM020370, Unclassified

DIRECTIONAL TECHNIQUE OUTLINE

**A. Techniques**

1. DARAS
2. ARRAYS
3. DIFAR

**B. Advantages**

1. False alarm rejection
2. Increased sensitivity
3. CFAR
4. Position
5. Velocity

**C. Implementation**

1. Methods of Processing Directional Information
2. System Design
  - a. LSD
  - b. Spectrum Analysis

## A. Directional Techniques

### 1. DARAS

DARAS, an acronym for Motorola's Direction and Range Active System is a technique for target detection and bearing estimation based on the processing of the time delay of a signal's arrival at three othogonally spaced microphones. As the name implies, DARAS was originally proposed for a sonar application. Original work on the use of a directional system to discriminate against aircraft was performed at NADC in 1968 and utilized a DARAS breadboard processor. This breadboard processor is still operational at NADC and can be used to verify many directional concepts, in fact this appears to be its biggest advantage. To operate optimally, DARAS requires a microphone spacing of  $\lambda/4$ ; 2.5 feet at 100 Hz. Because large SNR (Signal-to-Noise Ratios) are usually present, much smaller microphone spacings can be tolerated. High accuracy bearing estimates of truck movement have been measured at  $\lambda/25$ .

### 2. ARRAYS

Another possibility for directional systems are large element arrays. The main disadvantage of this technique is the large overall spacing that is required.

The use of cross correlations was investigated by AWG and the results suggest that bearing information on vehicles can be obtained and that perhaps vehicle counting and aircraft discrimination is possible. However, two buoys are needed to accomplish these tasks, implying limitations due to logistics considerations.

### 3. DIFAR

A directional technique that appears to hold promise in acoubuoy applications makes use of bigradient or cargradient microphones. The bigradient technique has been used extensively in ASW application (DIFAR). The main advantage of this technique is that it is relatively insensitive to frequency degradation, in addition, the microphone array and subsequent packaging remain small. The outputs of this particular directional technique are an omnidirectional channel, a directional channel whose response is proportional to the cosine of a source (signal) bearing, and another directional channel

whose response is proportional to the sine of the same source angle. To determine bearing, the sine and cosine channels are phase detected with the omni channel (to determine quadrant) and then the bearing angle is determined by an arctangent ratio. It appears that primary emphasis should be placed on the "gradient approach" because it appears more suitable for covert placement in an uncooperative area.

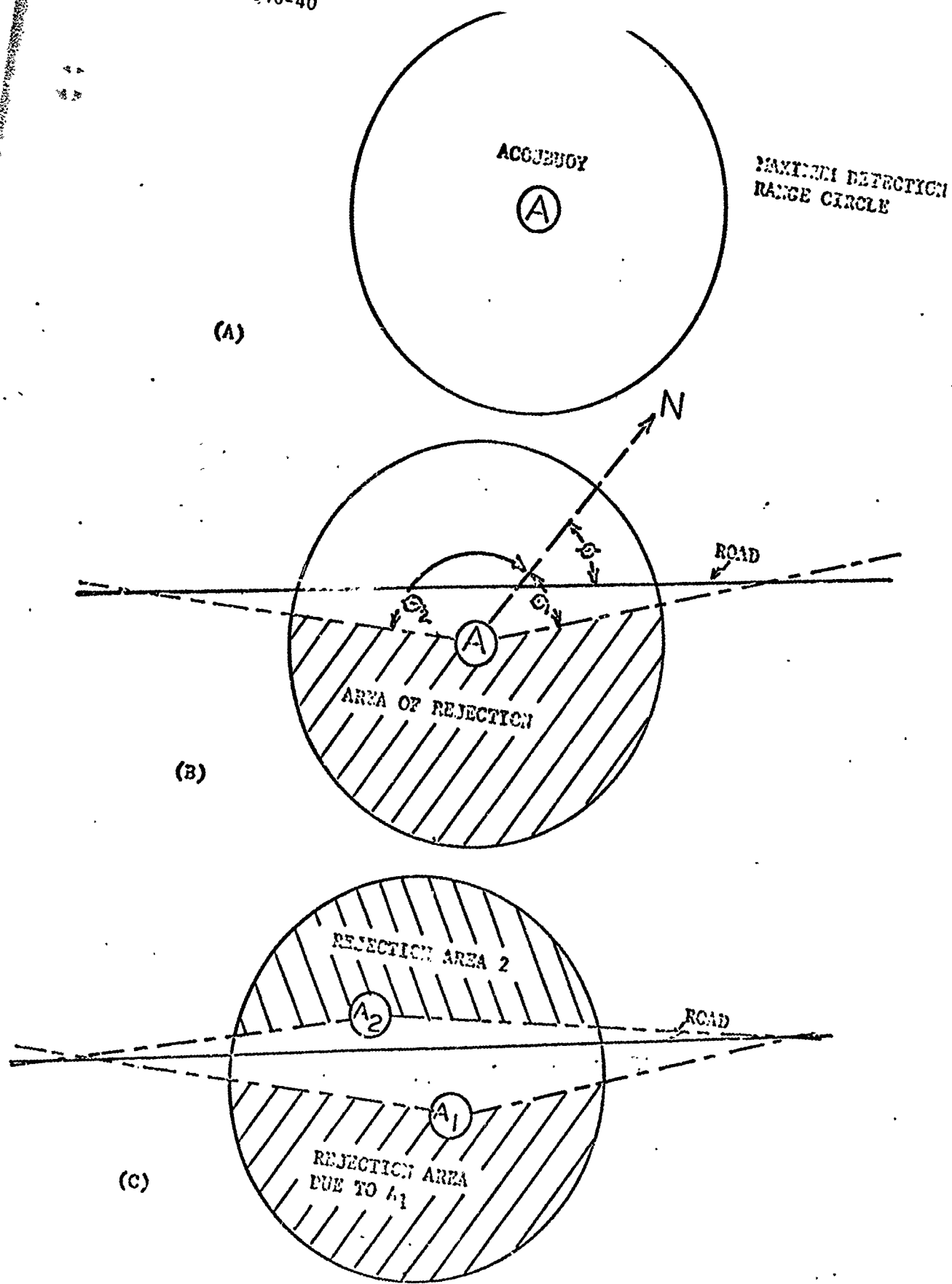
## B. Advantages of Directional System

### 1. False Alarm Rejection

One of the prime advantages of a DADS (Directional Acoubuoy Detection System) is the possibility of increased rejection of aircraft via directional information. Figure 1 shows an Acoubuoy with a maximum detection range circle. All vehicles (aircraft and trucks) within this circle will be detected by the Acoubuoy. If, however, a directional buoy is used, it would be possible to discriminate targets in the following manner. Assuming that the position of the buoy and road is known relative to magnetic north, simple logic could then reject targets lying in the hemisphere to the rear of the buoy. Hence, a simple test of computing a bearing and comparing it to a threshold device which requires the bearing to lie in the interval  $\theta_1$  to  $\theta_2$  could effectively be used. This simple procedure could eliminate all A/C not in the cone (determined by  $\theta_1$  and  $\theta_2$ ) as possible targets. If the A/C or other noise generator can be assumed to be uniformly distributed over  $360^\circ$  relative to the Acoubuoy, then  $\frac{\theta_2 - \theta_1}{360^\circ}$  of all false targets may be eliminated.

One fallacy of this argument (for in-buoy processing) is that the threshold circuit must know what cone ( $\theta_2 - \theta_1$ ) to compare the computed bearing against. One answer to this problem is to have Acoubuoy Reference Positioning capability and compute the exact location (in the aircraft or elsewhere). Once the orientation is computed a threshold value ( $\theta_2 - \theta_1$ ) may be radioed to the Acoubuoy via a command link. Another technique would use "a-priori" knowledge about the orientation of the road and manually set in the appropriate bearing window prior to deployment.

One method which might help to determine the appropriate bearing window to use as a threshold requires an aircraft to fly past the Acoubuoys of interest. With this method the Acoubuoy could compute



METHOD OF A/C REJECTION WITH DIRECTIONAL SYSTEMS

FIGURE 1

empirically the bearing window which then could be radioed via the command link. In addition to providing empirically determined threshold values, a calibrated aircraft could determine if Acoubuoys are working properly. The accuracies to which the position of the Acoubuoy and road are known relative to magnetic north are of paramount importance.

Use of this technique in truck parks would be limited because of loss of truck detections on the backside of the buoy or outside of threshold.

Added discrimination is possible if another Acoubuoy is placed on the other side of the road. Referring to Figure 1C, all aircraft behind the second Acoubuoy can be neglected. Hence, with two buoys all aircraft except those located in the small area of acceptability can be neglected. Aircraft which penetrate this area may be discriminated against by rate of change of bearing which for most aircraft would be excessive.

It is to be noted that the two buoy solution implies processing or correlation of data in the aircraft or the ISC. Further, once it is decided that a truck is present via the bearing threshold, it is possible at least conceptually, to transmit all lines detected back to a ground station and compute and relate all frequencies and bearing from a number of buoys.

## 2. Increased Sensitivity

The use of directional microphones offers the possibility of increased sensitivity through the manipulation of directional patterns. The sine and cosine patterns for a bi-gradient pair are given by:

$$F(\theta, \phi) = \sin \phi \cos \theta$$

$$F(\theta, \phi) = \sin \phi \sin \theta$$

Referenced to an omnidirectional microphone, they have a directivity gain of 4.77 db. Through manipulation of the three directional channels it is possible to electrically rotate cosine patterns and other more general patterns of the LIMACON family. The CARDIOD response is given by,

$$F(\theta) = \frac{1}{2} - \frac{1}{2} \cos \theta,$$

and has a D.I. of 4.77 db. The hyper CARDIOD whose response is given by,

$$F(\theta) = \frac{1}{4} - \frac{3}{4} \cos \theta$$

has a D.I. of 6 db.



This gain can be realized by sweeping or rotating the directional channels in the proper direction. The full gain may not be realized, because the signal is reduced from maximum gain (on-axis reception) depending on its orientation to the Acoubuoy. Normally, a number of beams, e.g., 4 (CARDIOD, HYPERCARDIODS, LIMACONS, etc.), are formed to look in all directions at once and reduce signal loss. If used in conjunction with detecting vehicles on a road, and if the orientation is known, perhaps only 2 beams need be formed. The main advantage of increased gain would appear to be in the location of trucks in parks.

It is also possible to manipulate the two directional channels by synthetic omni generation, or by taking the greatest of either the sine or cosine channels. It is possible to realize these gains without actually computing a bearing. However, the added complexity of these pattern combining techniques must be weighted against the actual improvement in system performance. The increase in range capability may be quite small.

### 3. CFAR

Since it is desired to perform detection in an Acoubuoy, thresholding schemes are very important. Most calculation of false alarm and detection probabilities assume that the noise intensity is known. This knowledge of noise intensity permits the decision threshold to be set to yield a specified false alarm probability. If the noise intensity is uncertain or variable, a fixed false alarm probability requires the addition to the detection system the means for measuring noise intensity. This noise measuring device can become quite complex and to avoid this complexity a means of providing detection without dependence on absolute levels is desirable. A directional system may have this capability of providing a level free method of thresholding. Under an ASW study contract SRRC (Sperry Rand Research Corp.) has proposed a technique, CFAR (Constant False Alarm Rate for ambient noise), which can be utilized with a three channel gradient system. If a three channel system is used, a quantity B, given by,

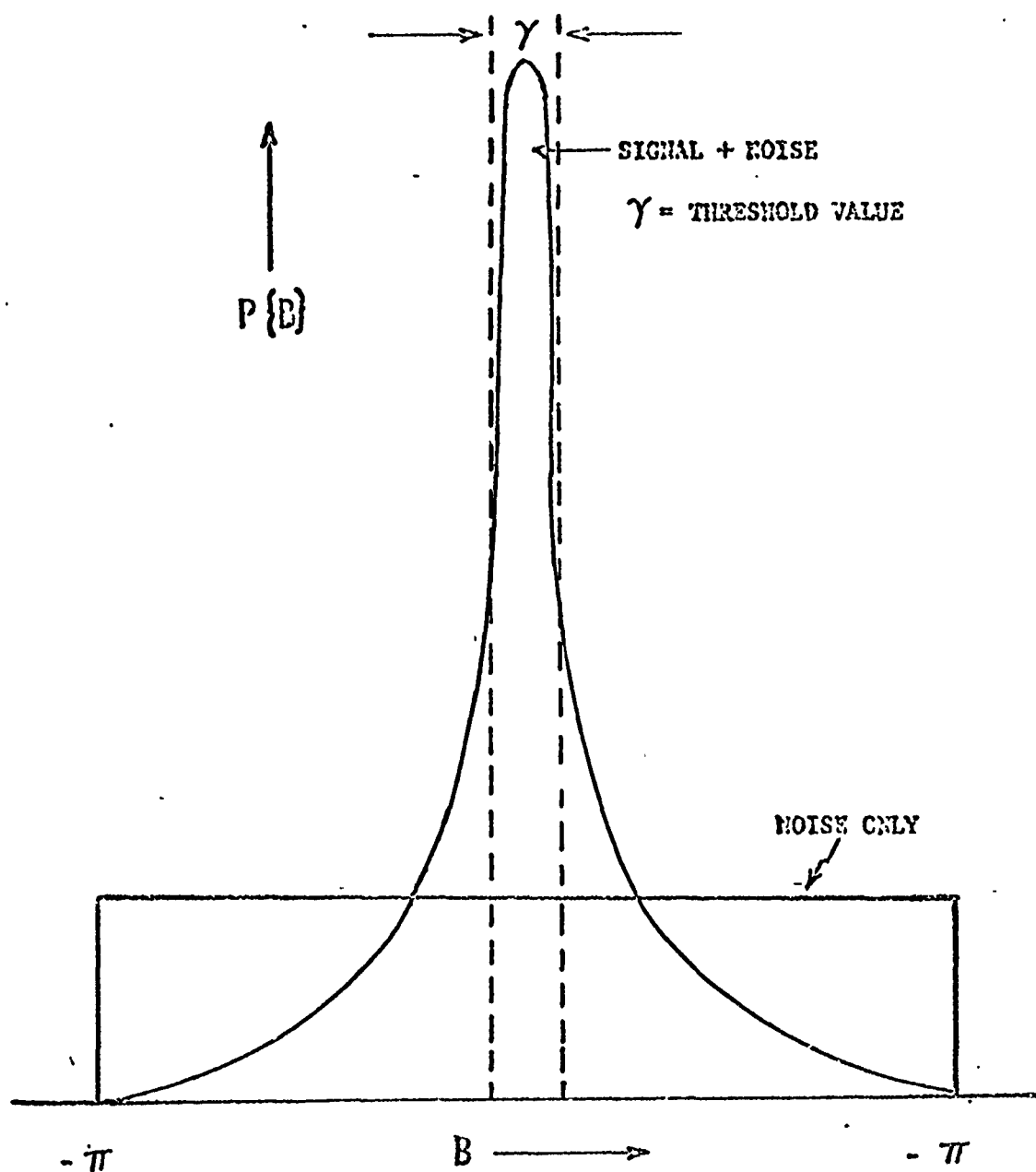
$$B = (\phi_1 - \phi_0) + (\phi_2 - \phi_0)$$

where:  $\phi_i$  are the analysis filter output phase angles given by,

$$\phi_i = \tan^{-1} \frac{M_{sn}}{N_{cn}} \quad n = 0, 1, 2$$

$\phi_i$  is the arctangent ratio of the quadrature and inphase components. can be calculated.

B is uniformly distributed in the interval  $-\pi$  to  $\pi$  for noise alone,



PROBABILITY DENSITY FUNCTION ( $P\{B\}$ ) FOR CFAR

regardless of its intensity (provided it is isotropic). A signal arriving from any bearing causes the probability density function of the signal plus noise to peak about zero with a sharpness that increases with SNR. A fixed threshold on the magnitude of B will provide a CFAR system as shown in Figure 2.

The actual performance of CFAR is speculated to be a few db poorer than for a threshold with accurately known noise intensity. SRRRC under a recently awarded ASW contract from NADC will determine actual performance, as well as a block diagram implementation of a CFAR system.

#### 4. Position

By triangulation between a directional system and the road offset and orientation or between two directional buoys, precise location of targets is possible. Target position error in either case will be a function of bearing accuracy and precise knowledge of buoy fix. A portion of this problem should be answered by the TI study on directional systems. A complication which may arise is the fact that the source of the bearing in the truck park may act like an extended source because of large area and number of trucks involved. Most theories which predict bearing accuracy consider only point sources of bearing.

#### 5. Velocity

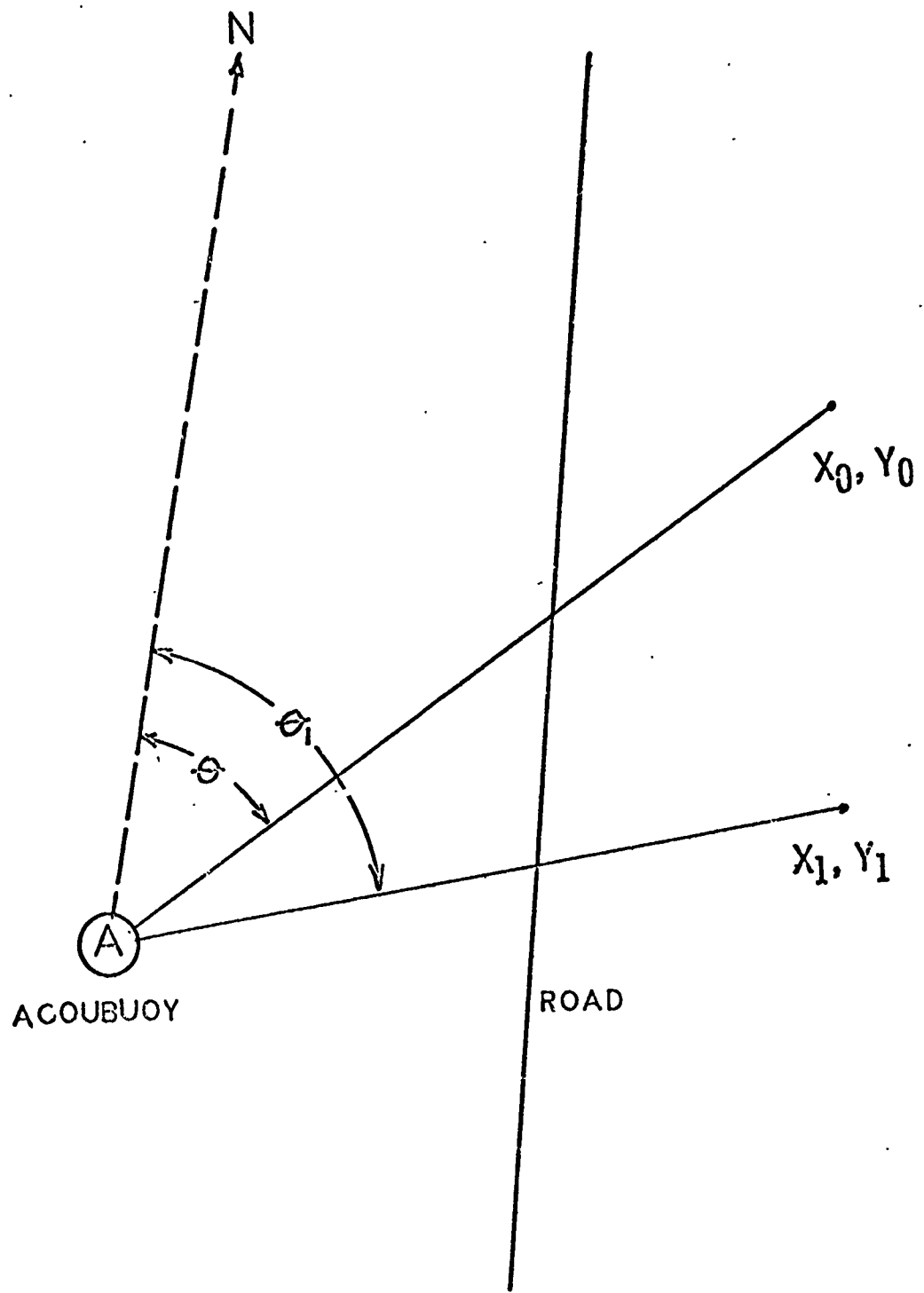
Originally, it was thought that the velocity difference between aircraft and vehicles could be used as a discriminant between the two. It was felt that an estimate of velocity could be derived by measuring the rate of change of bearing. Considering Figure 3, the rate of change of bearing,  $\frac{d\theta}{dt}$  is:

$$\frac{d\theta}{dt} = \frac{\partial\theta}{\partial x} \frac{dx}{dt} + \frac{\partial\theta}{\partial y} \frac{dy}{dt} = \frac{v_x y_1}{y_1^2 + x_1^2} - \frac{v_y x_1}{x_1^2 + y_1^2}$$

$$\theta_1 = \tan^{-1}\left(\frac{y_1}{x_1}\right) \quad v_x^2 + v_y^2 = v^2$$

$$y_1 = y_0 - v_y t$$

$$x_1 = x_0 - v_x t$$



## PROBLEM GEOMETRY

FIGURE 3  
G-10

From this it can be determined that:

(1) Rate of change of bearing is not a constant but varies with time.

(2) Maximum rate of change of a vehicle depends on its velocity and distance from the road and is given by:

$$\left(\frac{d\theta}{dt}\right)_{\max} = \frac{V}{CPA}$$

(3) Because the rate of change of bearing of an aircraft depends on so many variables (velocity, x and y coordinates), it is always possible to find a set which will be compatible with an expected or possible combination of vehicle parameters.

(4) It appears possible to discriminate between vehicle and aircraft on a rate of change basis by taking bearing differences and storing them (i.e., system must have memory). This amounts to plotting  $\frac{d\theta}{dt}$  vs time. Eventually an aircraft will probably depart from the expected maximum rate of change possible by a vehicle.

As can be seen from the above discussion, to determine velocity from bearing rate of change the distance from the road must be known. Another method of determining velocity is to compute the rate of change of position which is determined from two acoubuoys.

### C. Implementation

#### 1. Methods of Processing Directional Information

The basic bigradient or cargradient approach requires 3 channels of processing; one channel each for omni, sine and cosine channels. In general, some type of narrow band filtering is required for reasons which will now be explained. The main disadvantage of the gradient approach (DARAS also) is that this approach really provides no angular resolution. The bearing is computed by an arctangent ratio,

$$\theta = \tan^{-1} \left( \frac{y}{x} \right),$$

where: y and x are composite amplitude outputs.

If multiple targets, i.e., many trucks and/or aircraft, are present the amplitudes  $y$  and  $x$  are composite, hence the bearing derived is composite (vector sum) and is a weighted average of all frequencies (if broad band) and amplitudes present.

Unless it is possible to discriminate in time or frequency, bearing resolution is not possible. Discrimination can be accomplished in the frequency domain via narrow band filtering. Hence, the narrow band filtering of an LSD or a spectrum analyzer provides two advantages:

- (1) Increases the SNR of the line and hence improves bearing accuracy.
- (2) Separates lines so as to provide unbiased bearings and a bearing sort (possibility of a different bearing for each discrete frequency).

If two vehicles have the same frequency, then even narrow band filtering will not help and the bearing computed will be a composite. This may be a problem with closely spaced trucks in a convoy. Time discrimination is not possible since radiation generally is continuous and overlapping. As mentioned previously, the normal operation of a bigradient directional system requires 3 channels of processing. The obvious disadvantage of a 3 channel system is the added complexity relative to a one channel system. It is possible through the manipulation of the directional channels to have a two channel directional system. Two options are possible:

- (1) Two channel system with a bearing error equal to twice that of a 3 channel system.
- (2) Two channel system with the same bearing error as a 3 channel but ambiguous bearing of  $\pi$  radians.

The signals from the hydrophones can be represented as:

$$\text{OMNI} = A \cos (\omega_0 t - \phi)$$

$$\text{SINE} = A \sin \theta \cos (\omega_0 t - \phi)$$

$$\text{COSINE} = A \cos \theta \cos (\omega_0 t - \phi)$$

If we phase shift the sine channel by  $90^\circ$  [ $\sin (\omega_0 t + 90^\circ) = \cos \omega_0 t$ ] and add and subtract this channel to and from the cosine channel the following signals result:

$$A \cos \theta \cos (\omega_0 t - \phi) + A \sin \theta \sin (\omega_0 t - \phi) = A \cos (\omega_0 t - \phi - \theta)$$

$$A \cos \theta \cos (\omega_0 t - \phi) - A \sin \theta \sin (\omega_0 t - \phi) = A \cos (\omega_0 t - \phi + \theta)$$

The signals to be processed now consist of:

$$A \cos (\omega_0 t - \phi - \theta)$$

$$A \cos (\omega_0 t - \phi + \theta)$$

$$A \cos (\omega_0 t)$$

The bearing information,  $\theta$ , is now contained in the argument of the cosine wave. This procedure allows the use of a limiter in subsequent processing operations. If this technique were not used, the effect of limiter nonlinearities on the directional channels would cause significant bearing error.

As can be seen from the equations, the directional channels provide redundant information. The observation provides the basis for a two channel processing system. SRRC has investigated the performance of such a two channel system using just one of the directional channels and the omni channel. It was found that the bearing error (standard deviation) as compared to a 3 channel system is:

$$\sigma_{B2} = 2\sigma_{B3}$$

Hence, the total phase error, which is a sum of  $\sigma_s$  (system noise error) and  $\sigma_B$  (SNR dependent error) is given by:

$$\sigma_t^2 = \sigma_s^2 + 4\sigma_{B3}^2$$

For a three channel system:

$$\sigma_t^2 = \sigma_s^2 + \sigma_{B3}^2$$

Hence, how much a two channel system loses depends on  $\sigma_s$ . If  $\sigma_s$  is large enough, the difference between an two and three channel system may not matter.

The second 2 channel system requires the processing of both directional channels. This results in the same bearing error as a 3 channel system. However, a bearing ambiguity of  $180^\circ$  results. Whether or not this is acceptable depends on system usage.

## 2. System Design

The preceding paragraphs have set the stage for the functional design of a directional system. Two processing systems will be considered:

(a) LSD

(b) Spectrum Analysis

(a) LSD

The present receiver input bandwidth of the LSD system is 40 - 160 Hz. To compute a bearing on this broadband input which generally has a poor signal to interference ratio would be disastrous. It is possible to take the VCO output and use this signal as a reference with which to multiply the directional channels. It is felt that, in general, the signal (VCO) is too noisy to act as a coherent reference. Also, a phase shift is introduced between the VCO and input signal which when coupled with a noisy reference would produce a very poor bearing estimation system.

Some narrow band filtering should be performed in conjunction with the LSD function. A possible system configuration is shown in Figure 4. The input signal from the omnidirectional channel can be taken as,

$$\cos [\omega_0 t + \phi(t)]$$

where:  $\phi(t)$  is a random phase modulation.

The directional channel outputs are weighted by the response of the microphones as,

$$\cos \theta \cos [\omega_0 t + \phi(t)]$$

$$\sin \theta \cos [\omega_0 t + \phi(t)]$$

where:  $\theta$  is the source bearing angle.

Since the detection of signals in the directional channels will be angle dependent, the omnidirectional channel is used for LSD detection. Alternately, a synthetic omni could be used for detection but gains are very small for the equipment complexity needed. When a detection is made by the LSD, the frequency of the line being detected,  $f_0$ , is sent via the VCO or sweep generator to a mixer whose output frequency is  $(f_0 + f_v)$ . The signal is in turn heterodyned with the 3 incoming signals to produce outputs which are applied to 3 identical narrow band filters (NBF) which are tuned to  $f_0$ . In this way, the



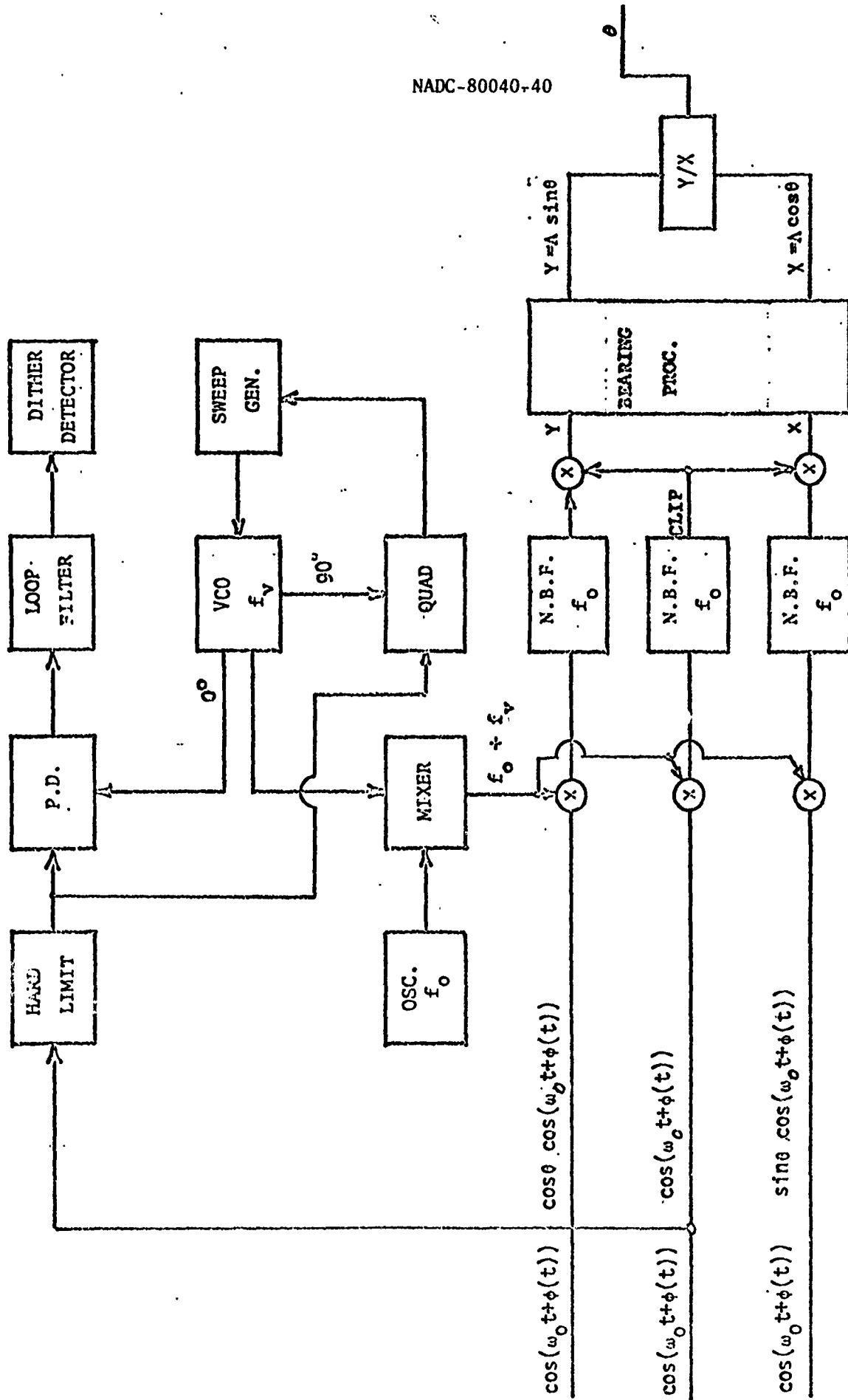


Figure 4  
Block Diagram Directional LSD (3 Channel)

spectral line of interest will always fall within the bandwidth of the NBF, regardless of how the incoming frequency varies. The outputs of the NBF are phase detected with the clipped omnidirectional signal and possibly integrated. Bearing is computed by,

$$\theta = \tan^{-1} \left( \frac{y}{x} \right)$$

The width of the NBF should be narrow enough to provide adequate gain against noise but wide enough to match the spectral spread of the lines and the error in the tracking of the line. The number of samples integrated depends on what rate of bearing change and resolution is needed for effective system operation (TI DADS output) and how much data can be transmitted over the R.F. link. The bearing accuracy and method of bearing computation will not be considered here. A two channel system is shown in Figure 5. A narrow band filter and integration are deleted and a 90° phase shifter is added.

Figure 6 shows the second possible two channel system. Only the directional channels are processed.

A problem exists with LSD operation when the outputs of two buoys are to be used. The nature of the LSD is such that it may possibly not lock on to the same line simultaneously at both acoubuoys. This would make correlation or triangulation of buoy outputs difficult, if not impossible. This problem arises because the LSD does not look at all lines simultaneously, as does a spectrum analyzer.

The spectral width of truck lines is estimated to be about 1 or 2 Hz. Theoretically the NBF can be made this narrow. The MDS level for the NL<sup>2</sup> acoubuoy is -18 db in a 1000 Hz band. The equivalent SNR in a 2 Hz band is +9 db. Integration of 6 samples (3 seconds) could increase the SNR to 13 db. The bearing accuracy attainable at this SNR is theoretically better than 5°.

#### (b) Spectrum Analysis

The general form of a directional spectrum analyzer is similar to the LSD. Figure 7 shows a top level block diagram. Three channels of spectrum analysis are needed. Two methods of spectrum analysis are being considered, a baseline hybrid deltic system and an FFT system. The hybrid design has been completed for a one channel system. For a directional system, the major changes would be in doubling of compression ratio and a time sharing of the analyzing filter by both directional channels. A 90° phase shifter and phase detection circuits would have to be added. For an FFT design, it is necessary to increase input buffer storage and speed requirements by three. Neither requirement appears to be excessive. A two channel system of the type previously discussed is simply a channel extension of a one channel system.

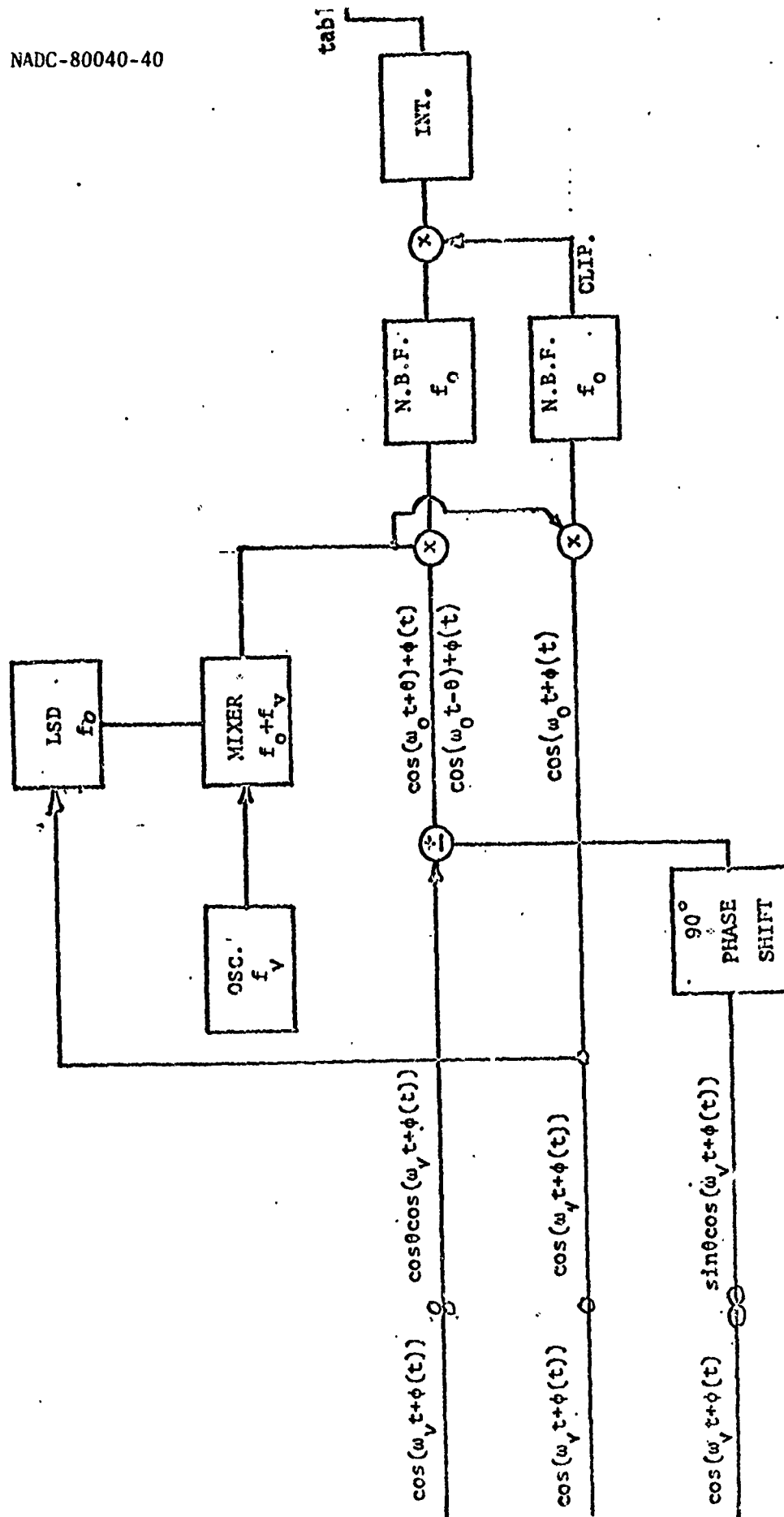


Figure 5.  
Block Diagram Directional LSD ( 2 Channel System)

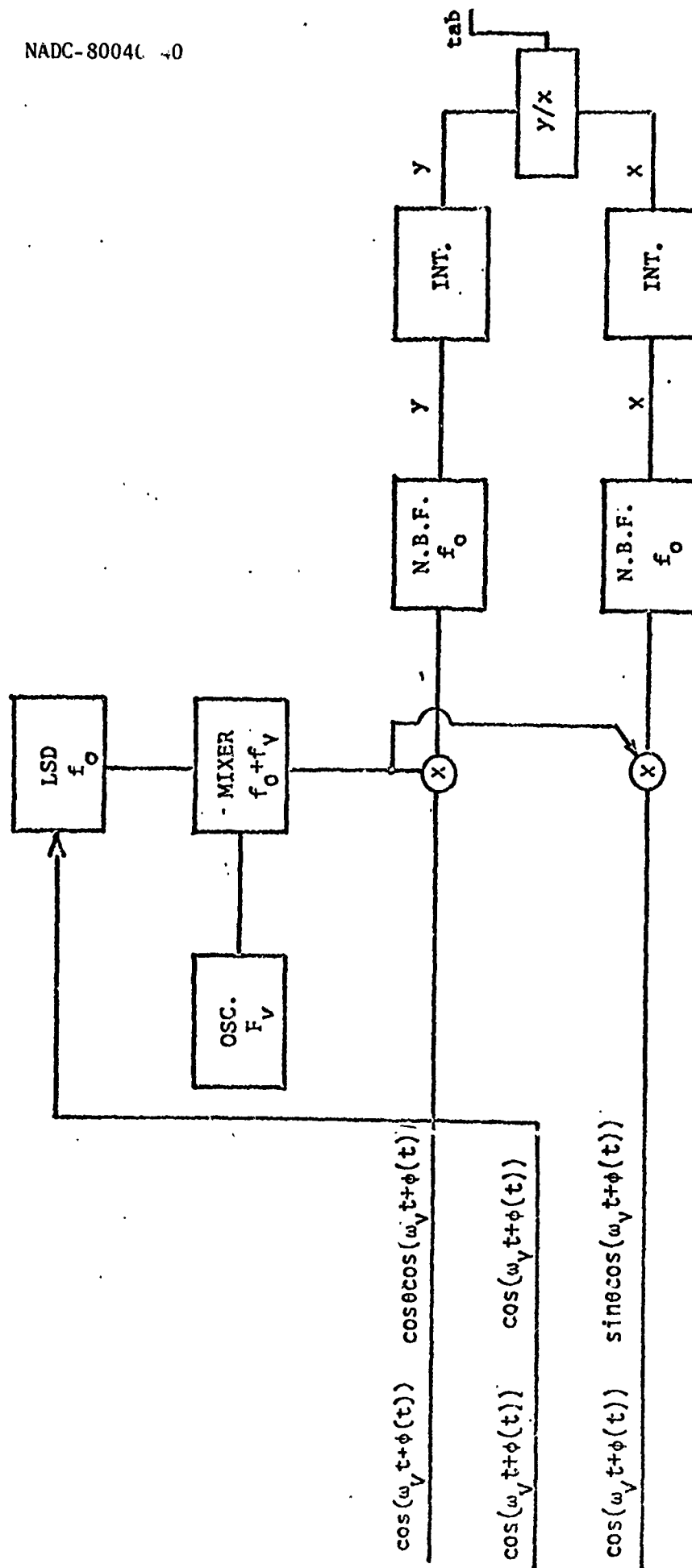


Figure 6  
Block Diagram Directional LSD System (2 Channel)

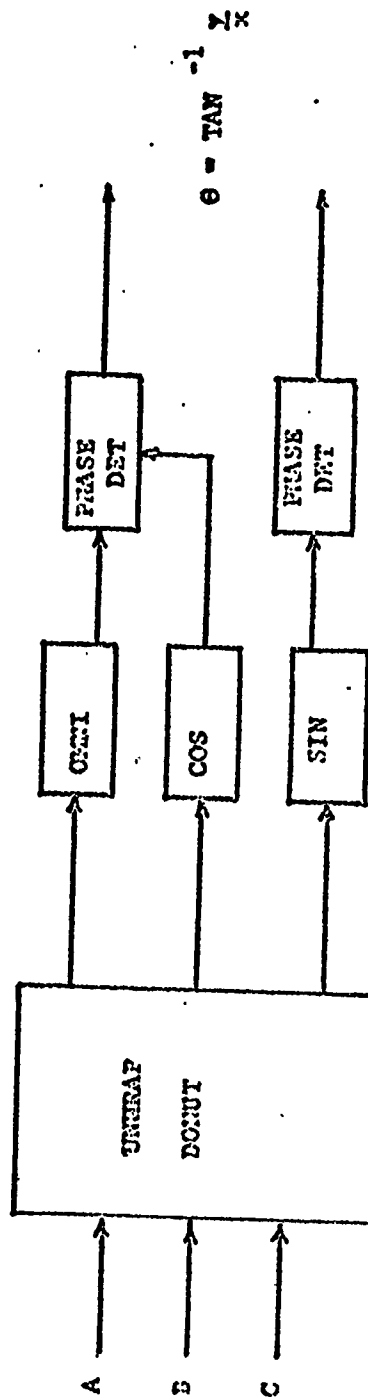
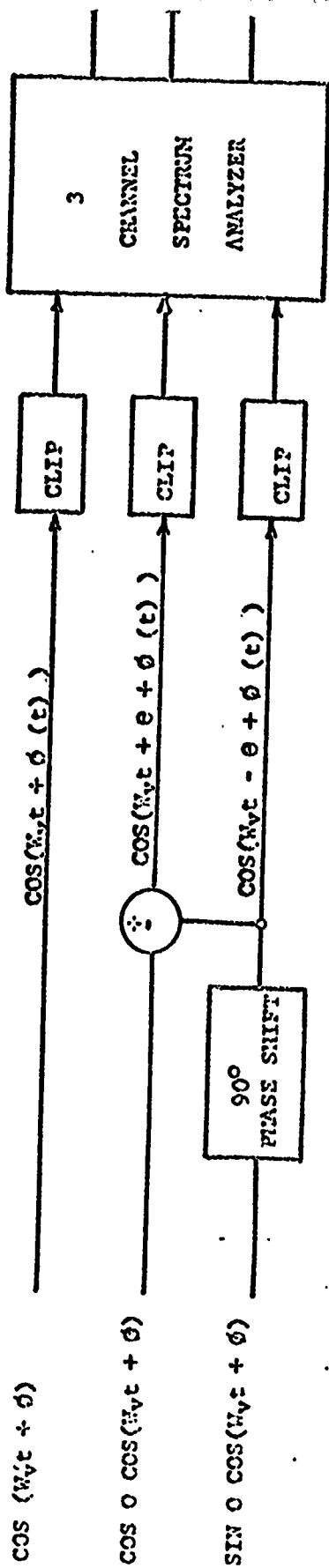


FIGURE 7

BLOCK DIAGRAM: DIRECTIONAL SPECTRUM ANALYZER SYSTEM

NADC-80040-40

APPENDIX H

Extracted from NADC Report #73046-50,  
26, Feb. 1972, (Unclassified)

## I N T R O D U C T I O N

One way a location of an acoustical emitting source can be determined is by knowing the sound pressure level at various known sensor locations, the propagation loss in the medium, and the output level of the source. Such knowledge at each sensor would allow appropriate range circles to be determined representing the loci of positions for the source. Figure 1 represents a typical location determination where  $S_2$  (sensor two) would be receiving a stronger signal than  $S_1$ ; similarly,  $S_1$  would be stronger than  $S_3$ .

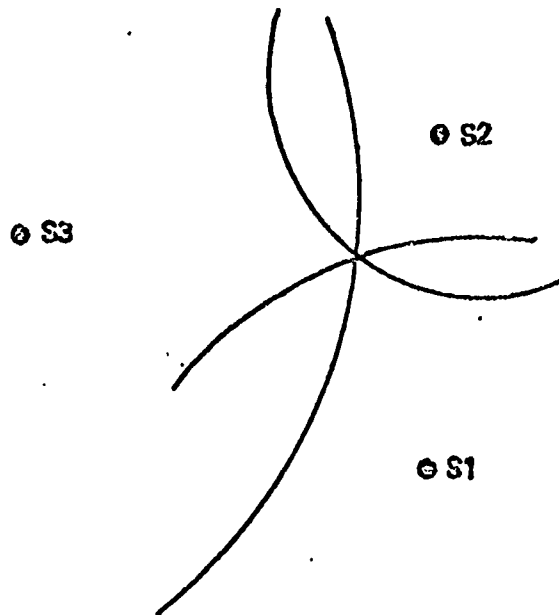


FIGURE 1 - Location by Three Range Circles

In general, a precise solution is not possible because of propagation anomalies, both temporal and spatial, and possible directivity from the sound source. In spite of this, often the resultant solution is an acceptable one, especially if tactically only general surveillance tracking is desired. When compared to other techniques for determining location, such as doppler tracking, use of directional sensors, hyperbolic fixing and the like, constraints as to the nature of the signal are very minimal (except for the unknown source directivity) i.e., either narrow or broadband signals, transient or continuous, can be used. In text there are two analytical approaches to this location determination technique, followed by a cursory simulation study, and the experimental results of a completely automated real time computer system which uses these signal strength techniques.

## DISCUSSION

Assume a sound source at an unknown location,  $P$ , which emits a signal, either continuous or transient, with an unknown level of  $S$ . When  $S$  is detected by three sensors at locations  $P_1$ ,  $P_2$ , and  $P_3$  with representative levels  $S_1$ ,  $S_2$ , and  $S_3$ , and the propagation loss is assumed to be expressed by some analytical function  $F_i(r)$ ,  $r$  being the range between the source and sensor  $P_i$ , then in general the SPL (Sound Pressure Level) in db of the sensor at  $P_i$  is

$$S_i = S - F_i(r). \quad (1)$$

In general, if the system is calibrated for signal strength from the sensor to the level measuring device, such as a meter at the output of a receiver, then three independent observations are sufficient for a location to be determined; i.e., two spatial coordinates along with the unknown source level; assuming that a two-dimensional space problem exists (a reasonable approximation in the open ocean). Though the propagation model is quite complex with spatial and time dependency, over a given period of time equation (1) can usually be simplified to be:

$$S_i(\theta, r, f) = A_i(\theta, f) + B_i(f, r) + C_i(f), \quad (2)$$

where

$$S_i(\theta, r, f)$$

is the received signal at some indicating device,

$$A_i(\theta, f)$$

the output level of a sound source, which is normally aspect angle and frequency sensitive,

$$B_i(r, f)$$

the propagation loss due to absorption and spreading losses, frequency and range dependent, while

$$C_i(f)$$

is the frequency dependent receiving system loss (or gain), dependent on the system parameters.



For discussion purposes, and one that is often quite reasonable under many operational conditions at the lower frequencies, the A term can be considered somewhat  $\theta$  independent, B replaced by  $-15 \log r_i$  (a compromise between spherical and cylindrical spreading loss), and  $C_i(f)$  only a function of frequency if similar sensors and a single receiver characteristic is used. With these understandings, equation (2) can be simplified to

$$S_i(r, f) = A(f) - 15 \log r_i + C(f). \quad (3)$$

In cartesian coordinates, the general desired solution has four unknowns: A, C, X, and Y where, because A and C can be considered as one variable, the solution can be further simplified to that of determining three unknown variables.

As mentioned earlier, solution of these three variables can be permitted by having three independent observations. Normally, this is done by three independent simultaneous (or near simultaneous) sensor observations at three different locations. Assuming three different sensor observations,  $S_1$ ,  $S_2$ , and  $S_3$  - equation (3) can be restated as

$$S_1 = A(f) - 15 \log r_1 + C(f), \quad (4)$$

$$S_2 = A(f) - 15 \log r_2 + C(f), \quad (5)$$

$$S_3 = A(f) - 15 \log r_3 + C(f). \quad (6)$$

By subtracting equations (5) and (6) respectively from equation (4), the result is two new equations:

$$S_1 - S_2 = 15 \log \left( r_2 / r_1 \right), \quad (7)$$

$$S_1 - S_3 = 15 \log \left( r_3 / r_1 \right). \quad (8)$$

In cartesian coordinates equations (7) and (8) become

$$S_1 - S_2 = 7.5 \log \left[ (X_2 - X)^2 + (Y_2 - Y)^2 \right] \left[ (X_1 - X)^2 + (Y_1 - Y)^2 \right]^{-1}, \quad (9)$$

$$S_1 - S_3 = 7.5 \log \left[ (X_3 - X)^2 + (Y_3 - Y)^2 \right] \left[ (X_1 - X)^2 + (Y_1 - Y)^2 \right]^{-1}. \quad (10)$$

Equations (9) and (10) are nonlinear in  $X$  and  $Y$ , but hopefully independent. It is desired to transform these equations into a form where  $X$  and  $Y$  are functions of the other variables or

$$X = F(X_1, X_2, X_3, Y_1, Y_2, Y_3, S_1, S_2, S_3), \quad (11)$$

$$Y = G(X_1, X_2, X_3, Y_1, Y_2, Y_3, S_1, S_2, S_3). \quad (12)$$

One method which allows the transformation of equations (9) and (10) into an approximate form of equations (11) and (12) uses a Taylor's series expansion with initial estimates of  $X$  and  $Y$ , where the process is iterated to give as accurate a solution as desired. Appendix A analytically describes a technique applicable to digital means of solving this type of problem.

The next obvious level of problem sophistication would be to have the coefficient of the composite spreading/absorption loss become a determined variable. While  $15 \log r$  was a compromise between spherical/cylindrical spreading and absorption, in general this is best considered a variable, dependent on range and bathothermic conditions. If this coefficient is allowed to be a determined variable, equations (9) and (10) become

$$2(S_1 - S_2) = D \log \left[ (X_2 - X)^2 + (Y_2 - Y)^2 \right] \left[ (X_1 - X)^2 + (Y_1 - Y)^2 \right]^{-1} \quad (13)$$

$$2(S_1 - S_3) = D \log \left[ (X_3 - X)^2 + (Y_3 - Y)^2 \right] \left[ (X_1 - X)^2 + (Y_1 - Y)^2 \right]^{-1}, \quad (14)$$

where  $D$  is an additional variable to be determined. It is now necessary to obtain one more independent equation to allow a solution to equations (13) and (14). Here, observations from sensor  $S_4$  will be considered resulting in

$$2(S_1 - S_4) = D \log \left[ (X_4 - X)^2 + (Y_4 - Y)^2 \right] \left[ (X_1 - X)^2 + (Y_1 - Y)^2 \right]^{-1}. \quad (15)$$

Equations (13), (14), and (15) can be solved in the same manner as mentioned above, with now initial estimates of  $X$ ,  $Y$ , and  $D$  required. One of the added benefits of this additional coefficient determination is that a simplified propagation model, based on experimental results, can be had; accurate to the initial assumptions of source omnidirectionality and spatial uniformity of the propagation modeling. The complexity of the propagation modeling could be increased as more independent observation are viewed. Such modeling is discussed in NAVAIRDEVCON Report

No. NADC-SD-7027 of 19 Jun 1970, "A Study of Using Multiple Nonlinear Regression Analysis for Acoustical Modeling." In addition, techniques such as simple data smoothing and Kalman filtering can improve the final solution, although the original assumption of source omnidirectionality and the stationary behavior of the medium and source is a practical limiting constraint. It is interesting to note that though geometrically and equally spaced sensors about a source give more accurate results, from a practical standpoint the placement of sensors in the same basic angular area, though geometrically poor, will tend to minimize errors due to angular variations. Finally the equivalent source level  $S$  itself can be determined if the absolute calibration of the system is known. This is done by substituting the results of either model back into equation (3), using the spreading coefficient 15 for the simplified model or the determined  $D$  for the more complicated model.

Though all of the above was based on some sort of system calibration reflecting the identical nature of the coefficient  $C$ , actually in the ocean this constraint can be overcome by taking advantage of the assumption that the basic sea state noise, at a given frequency in a localized area, would tend to be the same. Under these conditions, even if somewhat different broad system frequency and/or absolute levels occur, the difference of a given target source to sea state noise at a close by frequency would tend to be invariant to system parameters. Mathematically, for a given sensor system receiving sea state noise, this can be expressed as

$$N_i(f) = N(f) + C_i(f), \quad (16)$$

where  $N_i(f)$  is a measured sea state noise at a sensor,  $N(f)$  the sea state noise level and  $C_i(f)$  the system parameter. Now if equation (5) was not calibrated, i.e.,  $C(f)$  becomes  $C_i(f)$  and unknown, then by subtracting equation (16) from equation (3) (with  $C_i(f)$  vice  $C$ ) the result becomes

$$S_i(r, f) - N_i(f) = A(f) - N(f) - 15 \log r_i, \quad (17)$$

where though the absolute source level cannot be determined due to the presence of  $N(f)$ , solutions of spatial coordinate can still be manifested by expanding on equation (17) as was done for equation (3). Similarly for the more complicated four variable model, where an undetermined propagation loss coefficient was being determined, a similar result can be had.

Actually if care is taken to insure that only sea state noise is being measured where  $N_i$  is being determined, this technique overcomes some very practical constraints imposed by calibration. Limited tests on actual data reveal that this technique is operationally very reasonable and useable.

NADC-80040-40  
A COMPUTER SIMULATION EXAMPLE

To first determine the practicability of the forementioned approach of solving for both coordinates and a propagation model, two particular test cases were set up for computer simulation. Referencing figure 2, targets were considered at both points A and B to determine relative solution sensitivity for different geometries. Using an actual propagation model of

$$SPL = 50 - 20 \log r \quad (18)$$

where  $r$  is in kilometers, theoretical input data were generated for these two positions; four data points for each position. A FORTRAN program was written for the more complicated case as mentioned previously, where the propagation model was assumed to be of the form

$$SPL = A + B \log r, \quad (19)$$

and the determined variables are  $A$ ,  $B$ ,  $X$ , and  $Y$  ( $X$  and  $Y$  contained in the  $r$  term). Appendix B is the FORTRAN listing for this program where, using the design philosophy mentioned in appendix A, a digital solution to the problem was generated.

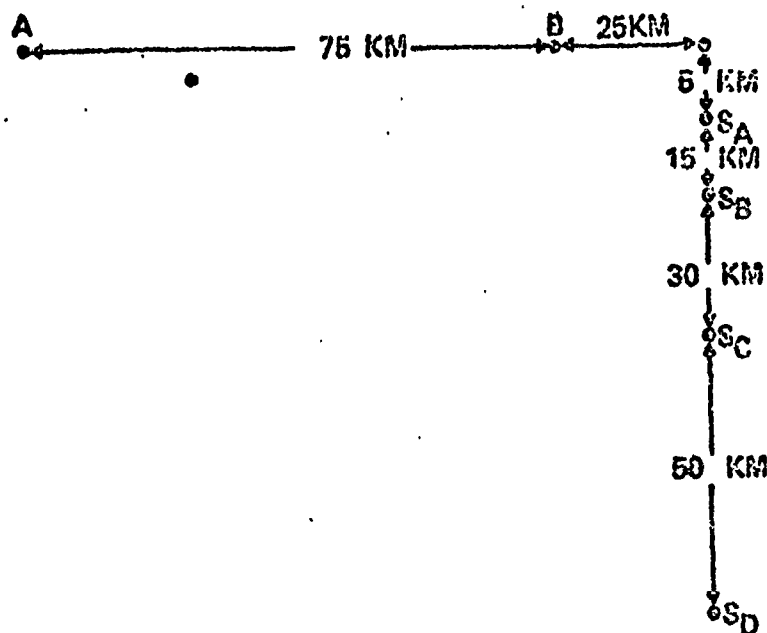


FIGURE 2 - Simulation Model

Using as input estimators for both test cases, points A and B, values of  $S = -40$  km,  $Y = +20$  km, and  $D = 30$ , the answers came out quite accurate as expected.

APPENDIX I

Excerpts from A Method of Obtaining Ranges of Aircraft  
From Lofar Gram Displays, NADC APS-2, 12 Jan. 1970  
TM011270, Unclassified

The doppler shifted frequency,  $f_D$ , of a radiated frequency,  $f_0$ , can be written as:

$$f_D = f_0 \left( \frac{C}{C - V_r} \right) \text{ for a moving source and stationary receiver.}$$

This equation can be rewritten as an approximation,

$$f_D \approx f_0 \left( 1 + \frac{V_r}{C} \right)$$

Where  $V_r = V_x \cos \theta$  and  $V_x = \text{speed}$  and  $\theta = \text{angle between the velocity vector and the radial component of that vector. Therefore:}$

$$f_D \approx f_0 \left( 1 + \frac{V_x \cos \theta}{C} \right)$$

#### DEFINITIONS:

1. Maximum up doppler =  $f_{D+} = \left[ 1 + \frac{V_x \cos \theta}{C} \right] f_0$  for small  $\theta$
2. Maximum down doppler =  $f_{D-} = \left[ 1 - \frac{V_x \cos \theta}{C} \right] f_0$  for small  $\theta$
3. Maximum difference in doppler shifted lines is

$$\Delta f_D = f_{D+} - f_{D-}$$

$$\Delta f_D = f_0 \left[ \left( 1 + \frac{V_x \cos \theta}{C} \right) - \left( 1 - \frac{V_x \cos \theta}{C} \right) \right]$$

$$\Delta f_D = f_0 2 \frac{V_x \cos \theta}{C} = 2f_0 \frac{V_r}{C} \quad (1)$$

The total distance traveled ( $2x$ ) during the time ( $2t$ ) in which the doppler shift changes from "maximum up" to "maximum down" is

$$2x = V_x 2t \quad \text{or}$$

$$x = \frac{C \Delta f_D t}{2f_0 \cos \theta} \quad (2)$$

and any distance  $x_0$  over which a change in doppler  $\Delta f_L$ , smaller than  $\Delta f_D$  will require a time  $t_0$ . From Figure (1) below, it is seen that,

$$\begin{aligned} x &= h \cos \theta \\ x_0 &= h_0 \cos \theta \end{aligned} \quad (3)$$

and

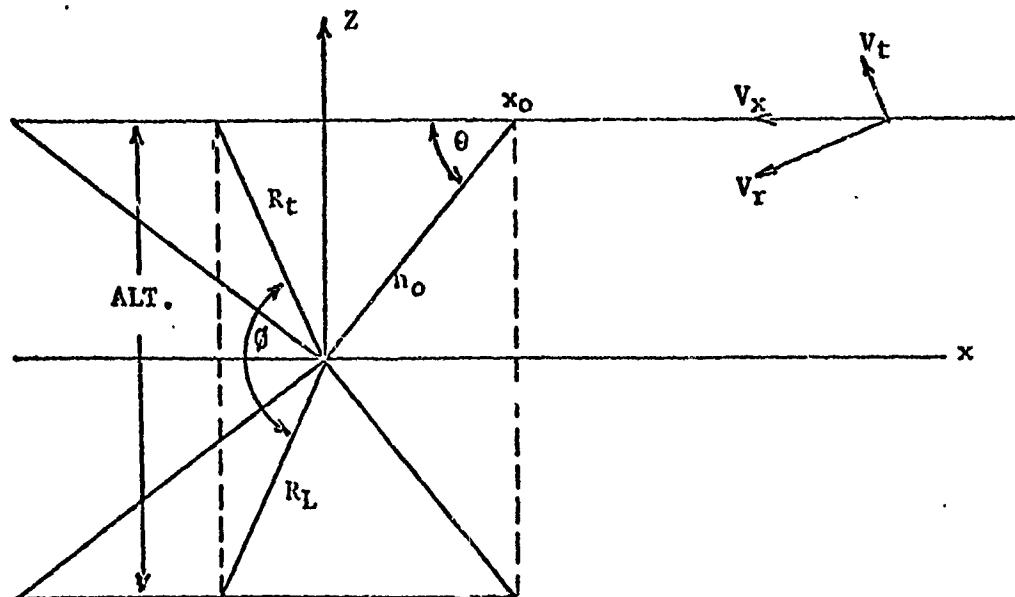
$$\cos \theta = \frac{x_0}{h_0} \quad (4)$$

$$\theta = \cos^{-1} \frac{x_0}{h_0}$$

Also from Figure (1), the slant range at CPA,  $R_T$ , can be written as

$$\begin{aligned} R_T &= h_0 \sin \theta \\ R_T &= h_0 \sin \left[ \cos^{-1} \frac{x_0}{h_0} \right] \end{aligned} \quad (5)$$

From equation (1), the total doppler shift ( $\Delta f_D$ ) is a function of the



velocity component pointing in the direction of the sensor ( $V_r$ ). This component, under the assumption of a straight line path along  $x$ , varies as a function of the cosine of the angle ( $\theta$ ) between the velocity vector ( $V_x$ ) and  $V_r$ . It can then be written that a small fraction of the total difference in doppler (up and down), centered about zero doppler ( $f_0$ ), is expressed as

$$(\Delta f_D)_0 = \cos \theta \Delta f_D$$

This quantity will be defined as

$$\Delta f_L = (\Delta f_D)_0 = \cos \theta \Delta f_D \quad (6)$$

Then

$$\cos \theta = \frac{\Delta f_L}{\Delta f_D}$$

and from equation (4),

$$\frac{x_0}{h_0} = \frac{\Delta f_L}{\Delta f_D}$$

and equation (5) can be written as:

$$R_T = h_0 \sin \left[ \cos^{-1} \frac{\Delta f_L}{\Delta f_D} \right]$$

Using equation (3) yields

$$R_T = \frac{x_0}{\cos \theta} \sin \left[ \cos^{-1} \frac{\Delta f_L}{\Delta f_D} \right] \quad (7)$$

Now, from equation (2), a small value of  $x$  called  $x_0$ , can be written as

$$x_0 = \frac{c}{2f_0 \cos \theta} \left[ \Delta f_D t \right]_0$$

The change in doppler over the path  $2x_0$  is  $(\Delta f_D)_0$  and by equation (6),



To obtain the lateral range from the slant range, then just requires writing

$$R_L = R_T \cos \theta$$

$$R_L = R_T \cos \left[ \sin^{-1} \frac{ALT}{R_T} \right]$$

$$RL = \frac{C \Delta f_D^2 t_o}{2f_0 \Delta f_L} \sin \left[ \cos^{-1} \frac{\Delta f_L}{\Delta f_D} \right] \cos \left[ \sin^{-1} \frac{ALT}{R_T} \right]$$

$$R_L = \frac{C \Delta f_D^2 t_o}{2f_0 \Delta f_L} \sin \left[ \cos^{-1} \frac{\Delta f_L}{\Delta f_D} \right] \cos \left[ \sin^{-1} \frac{2f_0 \Delta f_L ALT}{C \Delta f_D^2 t_o \sin \left( \cos^{-1} \frac{\Delta f_L}{\Delta f_D} \right)} \right] \quad (9)$$

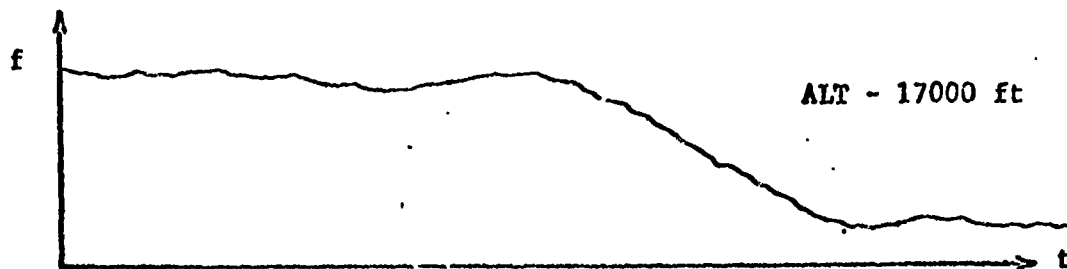
The value of  $\Delta f_D$ ,  $\Delta f_L$  and the corresponding time,  $t_o$ , are all obtainable from the AQA-5/7 gram display by the method shown in APPENDIX I.

From the values of these parameters,  $f_0$  and  $\theta = \cos^{-1} \frac{\Delta f_L}{\Delta f_D}$  (and therefore  $\sin \theta$ ) are calculable. The equation for the lateral range  $R_L$  can then be simplified to

$$R_L = \frac{C \Delta f_D^2 t_o}{2f_0 \Delta f_L} \sin \theta \cos \left[ \sin^{-1} \left( \frac{2f_0 \Delta f_L ALT}{C \Delta f_D^2 t_o \sin \theta} \right) \right] \quad (10)$$

APPENDIX ITYPICAL MEASUREMENTS OF  $\Delta f_D$  AND  $t_o$  WITH SAMPLE CALCULATIONS

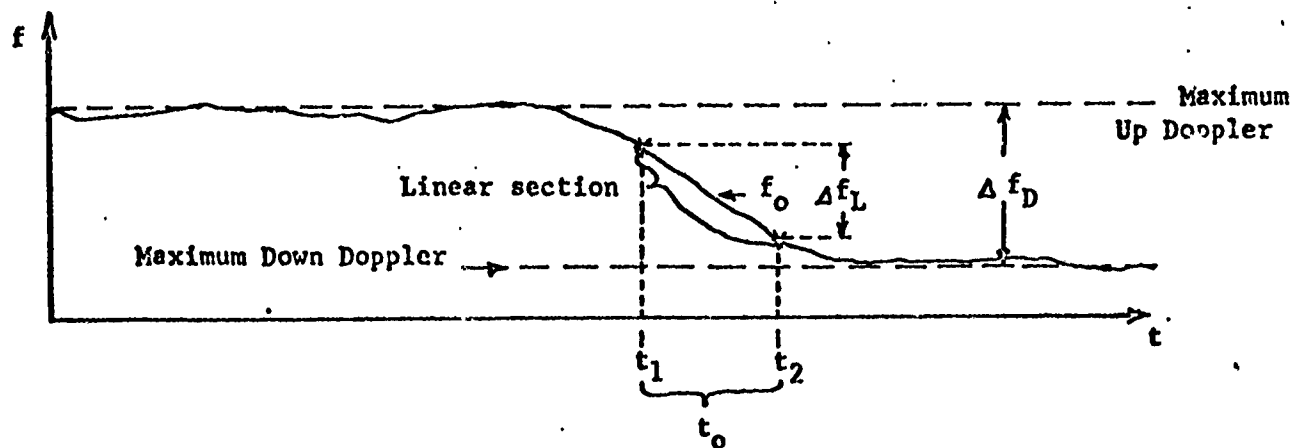
Suppose an AQA/5 gram displays information of the type depicted below.



A method of obtaining the range from this output is as follows:

1. Estimate the maximum up doppler ( $f_{D+}$ ).
2. Estimate the maximum down doppler ( $f_{D-}$ ).
3. Find the difference between (1) and (2) and call this  $\Delta f_D$ .
4. Choose a section of the doppler change line that is symmetric about  $\frac{f_{D+} + f_{D-}}{2} = f_0$  and call this section  $\Delta f_L$ .
5. Calculate the fraction of the total doppler change that the section of doppler chosen encompasses and call this fraction the value of  $\cos \theta$ .
6. Look up the value of the angle  $\theta = \cos^{-1} \frac{\Delta f_L}{\Delta f_D}$  and  $\sin \theta$ .
7. Find the difference between the two time values at which the chosen portion of the doppler change line terminates and call this  $t_o$ .
8. Plug in all necessary values to compute  $R_L$  from equation (9).

or (10). These points and values are noted on the sample gram below.



APPENDIX J

Excerpts from NADC Report # SD-7112

## DISCUSSION

There are various ways that the position of an emitter can be determined passively. The one that adapts itself to the location of a moving target having at least one discrete frequency is that which uses the knowledge of doppler shift at different sensor positions. It is readily apparent that with doppler shift being a function of range rate, and this in turn related to the course, speed, and location of an emitter relative to a sensor, it is possible to equate a series of relations for different sensors which could allow for the simultaneous evaluation of the various unknowns.

## DERIVATION

Before the generalized derivation is begun, the fundamental relationship of the observed frequency at a fixed sensor to an emission from a moving target need to be derived. Referencing figure 1 it is assumed that at time  $T_0$  the emitting source is at position  $L$ , while at  $T_1$  the source has moved to  $L_1$  and 1 cycle of the original waveform emitted at time  $T_0$  has transversed to  $M$ . Therefore the wavelength of the emitted radiation has been shortened, thereby raising the frequency to an observer at  $M$ .



FIGURE 1 - Doppler Geometry

This can be further equated by recognizing that the original frequency (without doppler shift) can be stated as being:

$$f_0 = v/\lambda = v/(L - M) \quad (1)$$

with  $v$  being the propagation velocity and  $\lambda$  the wavelength, while likewise the observed frequency at position  $M$  with doppler shift becomes:

$$f_1 = v/(L_1 - M). \quad (2)$$

Furthermore, the distance  $L - L_1$  can be equated to the product of target velocity  $V_T$  towards  $M$  and time, where the time for 1 cycle of  $f_0$  is  $1/f_0$ ; therefore the distance  $L - L_1$  becomes  $V_T/f_0$ , or rewritten as:

$$L_1 = L - (V_T/f_0). \quad (3)$$

Referencing equation (2) and substitution of equation (3) results in:

$$f_1 = v/[L - (V_R/f_0) - M]. \quad (4)$$

Utilizing equation (1), equation (4) can now be rewritten as:

$$1/f_1 = (1/f_0) - (V_R/vf_0), \text{ or } f_1 = f_0/[1 - (V_R/v)]. \quad (5)$$

If  $V_R \ll v$ , which is normally the case for acoustics, equation (5) can be rewritten as:

$$f_1 = f_0[1 + (V_R/v)]. \quad (6)$$

It is this relationship that will be useful for the generalized equation derivations.

Referencing figure 2,  $X_1, Y_1$  being a sensor location, and  $f_1$  as an observed frequency from the target source  $f_0$  located at position  $X, Y$  on a navigation course of  $\theta_1$  at a speed of  $V$ , the range rate  $V_R$  to the sensor is:

$$V_R = V \cos \theta_2, \quad (7)$$

which when combined with equation (6) results in:

$$f_1 = f_0[1 + (V/v) \cos \theta_2]. \quad (8)$$

Recognizing that:

$$\theta_2 = \theta_1 + \theta_3 + (\pi/2),$$

and that:

$$\theta_3 = \arctan (Y - Y_1)/(X - X_1),$$

then  $\theta_2$  becomes:

$$\theta_2 = \arctan (Y - Y_1)/(X - X_1) + \theta_1 + (\pi/2). \quad (9)$$

Equations (8) and (9) together relate to:

$$f_1 = f_0\{1 + (V/v) \cos [\arctan \{(Y - Y_1)/(X - X_1)\} + \theta_1 + \pi/2]\}, \quad (10)$$

which expresses mutually the unknowns,  $f_0$ , the target coordinates  $X, Y$ , and its course and speed,  $\theta_1, V$ . This relationship holds true for any quadrant relationship on the sensor and target if the proper quadrant relationship of the arctan is observed, i.e., if both the numerator  $Y - Y_1$  and denominator  $X - X_1$  are positive, the angle is between 0 and

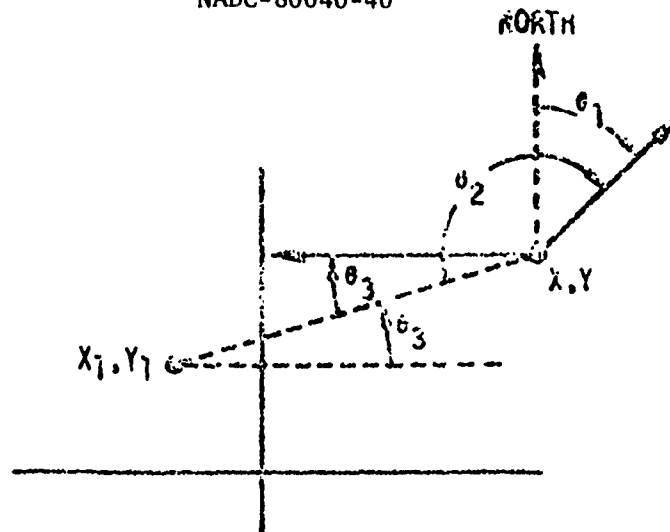


FIGURE 2 - Target, Sensor Geometry

$\pi/2$ , if the numerator is positive and the denominator is negative, and the angle is between  $\pi/2$  and  $\pi$ , etc.

In general, five independent observations at five sensors would be required to allow the determination of the unknowns in terms of the known values, i.e., the sensor coordinates, the doppler influenced frequency observations, and the propagation velocity,  $v$ . Often a more practical approach to the solution of the equations has two or three of the nominal unknowns approximated; the approximate solution formed on the remaining two unknowns being normally the location coordinates. This approach becomes very useful where, as for many practical cases, no assurance can be had that five sensors will ever detect the target's emission.

## SOLUTIONS

The first particular philosophy for solution of target location which is investigated is that where values of  $f_0$ , course and speed, are assumed known, at least approximately, from other intelligence; this philosophy requires only two simultaneous sensor detections. The second philosophy investigated assumes that no precise information is known on any of the parameters, but the doppler frequency is observed simultaneously at five sensors. Unlike the first case, where an exact solution can be derived, the complexity of the second case results in the use of iterative techniques approximating a solution to any desired accuracy. Appendixes A and B are the computer listings for the two sensor and five sensor programs, respectively.

The solution of target location, assuming only two sensors are detecting, can be accomplished by rewriting equation (10) as:

$$\arccos [v(f_1 - f_0)/f_0 V] = \arctan (Y - Y_1)/(X - X_1) + \theta_1 + (\pi/2), \quad (11)$$

or simplified to:

$$\tan \{-(\pi/2) - \theta_1 + \arccos [v(f_1 - f_0)/f_0 V]\} = (Y - Y_1)/(X - X_1). \quad (12)$$

Defining the left-hand side as  $Q_1$ , equation (12) can be rewritten as:

$$Q_1 X - Q_1 X_1 = Y - Y_1, \text{ or } Y - Q_1 X = -Q_1 X_1 + Y_1. \quad (13)$$

Again the simultaneous observation at a sensor  $X_2, Y_2$  allows a second equation to be written as:

$$Y - Q_2 X = -Q_2 X_2 + Y_2, \quad (14)$$

where:

$$Q_2 = \tan \{-(\pi/2) - \theta_1 + \arccos [v(f_2 - f_0)/f_0 V]\}. \quad (15)$$

By subtracting equation (14) from (13), one obtains:

$$X = (-X_1 Q_1 + X_2 Q_2 + Y_1 - Y_2)/(-Q_1 + Q_2), \quad (16)$$

while with the other coordinate  $Y$  determined by substituting equation (16) with equation (13), or:

$$Y = -Q_1(X_1 - X) + Y_1. \quad (17)$$

Unfortunately, equations (16) and (17) do not normally give unique solutions. This is related to the fact that the arccos factors of equations (12) and (15) are multivalued. This can be appreciated by an understanding of the geometry of the problem and how it relates to the forementioned solutions. Referencing figure 3 as a typical example of geometry, it can be seen that for the sensors  $P_1$  and  $P_2$ , assuming a known  $f_0$ , course and speed, the intersection of the sensor range-rate lines describe the possible target,  $P$ , solutions.

In particular, half-lines A and B represent the possible locations that the target  $P$  could be on and satisfy the fundamental doppler relationships for sensor  $P_1$ , where the half-lines have as their bisector a line parallel to the course of the target and one of the half-lines going through the target's position. If the target is anywhere on these lines with the same course and speed, the observed doppler shift at the sensor is the same anywhere on these two half-lines. Similarly, the same is true for sensor  $P_2$  and its half-lines C and D. The intersection of these



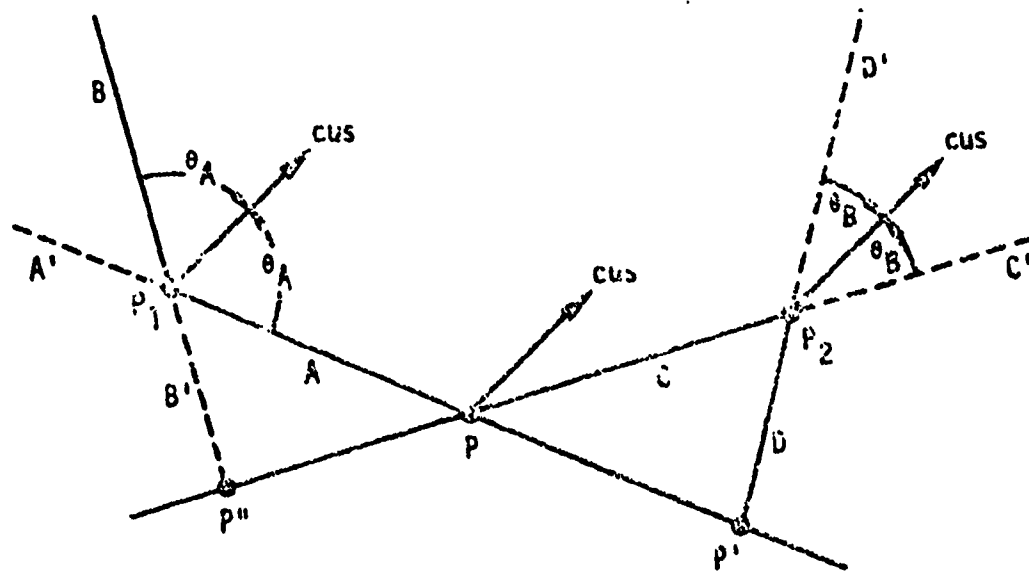


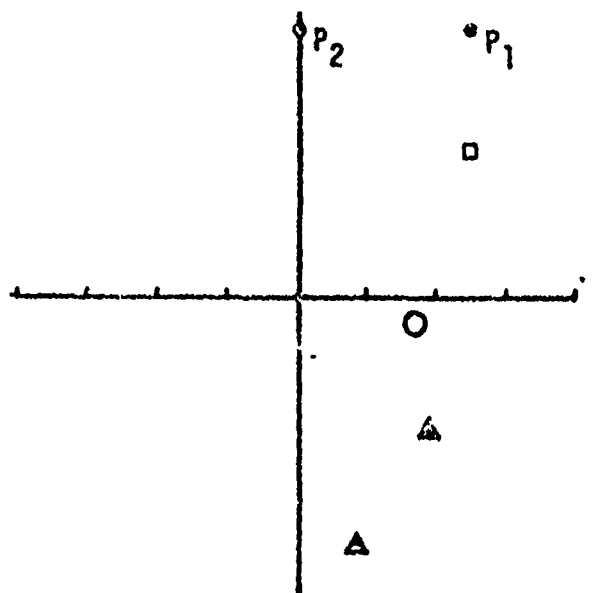
FIGURE 3 - Target Redundancy Geometry

lines for this geometry allows the solution of  $P$  and  $P'$ . In this case, these two solutions can be equated to using two different, and both proper, values for the arccos function of equation (15).

In addition, the problem can be further complicated by the fact that with the cosine function being even valued, an improper sign can be attached to the arccos function. This relates to the equivalent of using doppler information with a wrong sign value, or geometrically to using the extensions of the half-lines; in figure 3, these being  $A'$ ,  $B'$ ,  $C'$ , and  $D'$ . Again, for our geometry this combination can result with a fix at  $P''$ . Finally, a fourth intersection would also occur for this geometry by the intersection of  $B'$  and  $D$ . In general, four possible fixes can be obtained by using the multivalued options of the arccosines; two proper and two improper fixes.

Fortunately, there exists rather simple computational procedures, most appropriate for computer computation, which resolve both problems; i.e., the selection of the "proper" fix and elimination of the improper fixes. By solving for all four possible combinations of equation (16) and (17), using both the positive and negative principle angles for the arccosine computation used in determining  $Q_1$  and  $Q_2$ , assurance is guaranteed that the proper solution exists. By recognizing that the coordinates of the improper fixes will give some calculated doppler shifts reversed from the observed, one can eliminate the improper fixes. Calculating equation (10) for both  $P_1$  and  $P_2$  with the improper fixes coordinates will result in at least one determination of a doppler shift  $(f_1 - f_0)$  or  $(f_2 - f_0)$  which is reversed in sign from the original input values. Referencing figure 3,  $P''$  would give a proper doppler check for  $P_2$ , but improper for  $P_1$ . Determination of which of the two proper fixes is appropriate can only be done at this point by assuming an approximate location of the target and using that fix which is closest to it.

To check qualitatively the location sensitivity of the program, the assumed input parameters were systematically changed from the proper input target parameters. Figure 4 exemplifies the results of some typical examples tried for the two sensor programs, where  $P_1$ ,  $P_2$  are two sensor locations, the solid triangle denotes the position of the actual target and also the fix determined by the two sensor programs for exact course, speed, and  $f_0$ . For these examples there was a course of 60 degrees at 25 knots,  $f_0$  of 100 Hertz. The non-filled symbols of triangle, square, and circle reflect the position determined by the two sensor programs when the target sequentially had  $f_0$ , course, and speed different from the target true parameter. The behavior of position accuracy as a function of input errors becomes evident by noting the displacement caused by an error in  $f_0$ , course, and speed. In general, unless rather accurate estimates are made of the three approximate inputs, the location accuracy can become quite poor.



- Δ Original target location
- Δ +0.1-percent  $f_0$  error, 2 sensors
- +30-degree heading error, 2 sensors
- +20-percent speed error, 2 sensors

FIGURE 4 - Location Versus Input Parameters Errors, Two-Sensor Program

The second philosophy to be investigated assumes that five-sensor information is known. Here, in considering solutions for more than two sensor inputs, another analytic technique will be explored. An iterative process will be used, where derived appropriate linear expressions replace the complex doppler equations, with the dependent variables  $X$ ,  $Y$ , and  $f_0$ ; course and speed are simply expressed in terms of the known variables - the sensor positions and the observed sensor frequencies. Mathematically this can be stated as a transformation of the original equations, which is of the general form of equation (10), or:

$$f_i = F(P_i, P, \text{course}, \text{speed}, f_0), \quad (18)$$

where  $f_i$  is the doppler frequency at sensor  $P_i$  receiving an emitting frequency from a target located at  $P$  traveling on a course and speed. This functional relationship is now desired to be transformed into a more usable matrix form of:

$$\bar{Z} = F([\bar{f}_i, P_i]) \quad (19)$$

where  $\bar{Z}$  are the desired independent variables,  $X$ ,  $Y$ , course, speed, and  $f_0$ . One such analytical method that allows this transformation is a modified form of a Taylor's expansion, which also adapts itself readily for digital computation. Classically, normal linearization would give a form of:

$$\bar{Z} = \bar{A} + \bar{B}f_1 + \bar{C}f_2 + \bar{D}f_3 + \bar{E}f_4 + \bar{F}f_5, \quad (20)$$

where  $f_1$  through  $f_5$  are the observed doppler frequencies at five sensors. The coefficients  $\bar{A}$  through  $\bar{F}$  are determined coefficients, dependent upon expansion points and the desired independent variables. Because of computational simplification resulting in a solution independent of  $f_0$ , it becomes more convenient to change equation (20) into:

$$\bar{Z} = \bar{A} + \bar{B}(f_1/f_2) + \bar{C}(f_1/f_3) + \bar{D}(f_1/f_4) + \bar{E}(f_1/f_5). \quad (21)$$

To derive the appropriate coefficients of equation (21), it is assumed that vector  $\bar{Z}$  can be described by a 4x1 matrix:

$$\bar{Z} = \begin{bmatrix} X \\ Y \\ C \\ V \end{bmatrix} \quad (22)$$

where  $X, Y$ , are coordinates, and  $C, V$ , are course and speed respectively. Likewise, the determined coefficients of the linear equations can also be described by the 4x5 matrix:

$$\begin{bmatrix} A_x & B_x & C_x & D_x & E_x \\ A_y & B_y & C_y & D_y & E_y \\ A_c & B_c & C_c & D_c & E_c \\ A_v & B_v & C_v & D_v & E_v \end{bmatrix} = \bar{G}. \quad (23)$$

Finally, the independent variables can be described by the 5x1 matrix:

$$\begin{bmatrix} 1 \\ R_2 \\ R_3 \\ R_4 \\ R_5 \end{bmatrix} = \bar{R}, \quad R_i = f_i/f_1 \quad (24)$$

where  $f_1, f_i$  are observed frequencies.

The total relationship in matrix form can be written as:

$$\bar{Z} = \bar{G} \bar{R}, \quad (25)$$

where in the final form  $\bar{Z}$  is being determined as a function of  $\bar{G}$  and  $\bar{R}$ .

To determine  $\bar{G}$ , an ancillary set of equations must be solved, which assumes an expansion point for  $X, Y$ , course, and speed, and by using difference equations, allows for the solution of  $\bar{G}$ . By defining the calculated quantity:

$$Q_i = \frac{1 + (V/v) \cos [\arctan \{(Y - Y_1)/(X - X_1)\} + (\pi/2) + \theta_1]}{1 + (V/v) \cos [\arctan \{(Y - Y_i)/(X - X_i)\} + (\pi/2) + \theta_1]} \quad (26)$$

and  $Q_{ix}$  as meaning  $Q_i$  only with using  $X + \Delta X$  vice  $X$  as an expansion point, and similarly for subscripts  $y, c, v$ , the determining coefficients sequentially being  $Y + \Delta Y, C + \Delta C$ , and  $V + \Delta V$ , the matrix  $\bar{Q}$  is defined to be the 5x5 matrix:

$$\begin{bmatrix} 1 & Q_2 & Q_3 & Q_4 & Q_5 \\ 1 & Q_{2x} & Q_{3x} & Q_{4x} & Q_{5x} \\ 1 & Q_{2y} & Q_{3y} & Q_{4y} & Q_{5y} \\ 1 & Q_{2c} & Q_{3c} & Q_{4c} & Q_{5c} \\ 1 & Q_{2v} & Q_{3v} & Q_{4v} & Q_{5v} \end{bmatrix} = \bar{Q}. \quad (27)$$

By defining the 5x1 matrix  $\bar{G}_1$  as:

$$\begin{vmatrix} A_i \\ B_i \\ C_i \\ D_i \\ E_i \end{vmatrix} = \bar{G}_i, \quad (28)$$

the individual  $\bar{G}$  terms can be determined by standard simultaneous linear equations for the following expressions:

$$\bar{Q} \bar{G}_x = \begin{vmatrix} X \\ X + \Delta X \\ X \\ X \\ X \end{vmatrix} \quad (29)$$

$$\bar{Q} \bar{G}_y = \begin{vmatrix} Y \\ Y + \Delta Y \\ Y \\ Y \\ Y \end{vmatrix} \quad (30)$$

$$\bar{Q} \bar{G}_c = \begin{vmatrix} C \\ C \\ C + \Delta C \\ C \\ C \end{vmatrix} \quad (31)$$

$$\bar{Q} \bar{G}_v = \begin{vmatrix} V \\ V \\ V \\ V + \Delta V \\ V \end{vmatrix} \quad (32)$$

where the appropriately determined  $\bar{G}_i$  coefficients can now be substituted into equation (21).

The forementioned procedure can be considered a modified form of Taylor's expansion about a point X, Y, C, and V, if the deltas are sufficiently small enough. In practice, the question of initial accuracy is not too important if an iterative form of solution is used; i.e., the initial expansion point is replaced by the resultant solution and iteratively solved until the changes in all solution between two iteratives are below a certain percent - such as 1 percent. As in any iterative mathematical procedure, the question of solution convergence must be addressed. In general, if any reasonable input information is known, the solution will converge.

NADC-80040-40

APPENDIX K  
Excerpts from NADC Report # SD-6814  
of 7 Feb. 1970, (Unclassified)

# DERIVATION OF SOURCE LOCATION EQUATION

To derive relationships for determining the position of a sound source, and for simplicity, it is assumed that the sound arrival time and the sensor locations are known, and that a two-dimensional physical geometry problem exists. This dimensionality requires that a plane be drawn through the sensor and source locations, a situation that occurs essentially when the distances among the sensors and the sound source are large compared to any height variations.

With only the sound arrival times,  $T_1$ ,  $T_2$ , etc, at the sensors known (and the initial emission time unknown), a meaningful measurable quantity that readily adapts itself to locating the sound source is the time difference  $\Delta T$  in the sound arrival times at the sensors. With these inputs, relationships can be derived to express the difference in distances  $\Delta D$  between the source  $P(X, Y)$  and any two sensors. For example, using  $P_1(X_1, Y_1)$  and  $P_2(X_2, Y_2)$  in figure 1, one can derive:

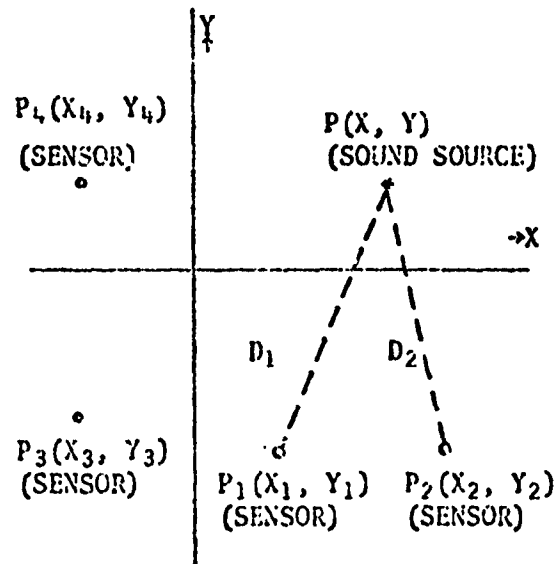


FIGURE 1

$$[(X - X_1)^2 + (Y - Y_1)^2]^{1/2} - [(X - X_2)^2 + (Y - Y_2)^2]^{1/2} =$$

$$D_1 - D_2 = \Delta D_{12} = (T_1 - T_2)V = \Delta T_{12}V, \quad (1)$$

where  $\Delta D_{12}$  is the difference in distances between  $P_1$ ,  $P$  and  $P_2$ ,  $P$  (positive when  $D_1 > D_2$ ), and  $V$  is the velocity of sound ( $\approx 340$  meters per second in air depending upon atmospheric conditions).

Equation (1) results in a family of hyperbolic lines, and recognizing that two equations and two unknowns are needed to solve for  $P$  (three if the two-dimensional constraint is not imposed), another relationship must pertain. This can be a relationship similar to equation (1) except for different sensor locations, say  $P_3$ ,  $P_4$ . Thus:

$$[(X - X_3)^2 + (Y - Y_3)^2]^{1/2} - [(X - X_4)^2 + (Y - Y_4)^2]^{1/2} = \Delta T_{34}V. \quad (2)$$

The basic relationships now exist in equations (1) and (2) to allow a solution, with the additional realization that only three unique sensor

positions are needed, and nothing prevents one of the sensors in equation (1) being that of equation (2), such as  $P_2 = P_3$ .

It is possible that a nonunique solution exists for these equations, an example being when the sensors are located nearly in line with each other, allowing the hyperbolas to intersect at two positions. One approach that allows the equations to be solved with a unique solution is to put them into linear format and solve these new pseudo equations by Cramer's rule. This is done by expanding equations (1) and (2) by a Taylor expansion in two variables about an assumed point close to  $P$ . Taylor's expansion for two variables about a hypothetical point  $a_x, a_y$  becomes:

$$F(X,Y) = F(a_x, a_y) + \frac{\partial F}{\partial X} \bigg|_{a_x, a_y} (X - a_x) + \frac{\partial F}{\partial Y} \bigg|_{a_x, a_y} (Y - a_y) \dots \quad (3)$$

where all terms, second order and above, are ignored.

By this expansion, equation (1) now becomes:

$$\begin{aligned} & [(a_x - X_1)^2 + (a_y - Y_1)^2]^{1/2} - [(a_x - X_2)^2 + (a_y - Y_2)^2]^{1/2} \\ & + (a_x - X_1)(X - a_x)[(a_x - X_1)^2 + (a_y - Y_1)^2]^{-1/2} \\ & - (a_x - X_2)(X - a_x)[(a_x - X_2)^2 + (a_y - Y_2)^2]^{-1/2} \\ & + (a_y - Y_1)(Y - a_y)[(a_x - X_1)^2 + (a_y - Y_1)^2]^{-1/2} \\ & - (a_y - Y_2)(Y - a_y)[(a_x - X_2)^2 + (a_y - Y_2)^2]^{-1/2} = \Delta T_{12}V. \end{aligned} \quad (4)$$

This can be simplified by defining  $A_m = [(a_x - X_m)^2 + (a_y - Y_m)^2]^{1/2}$ ,  $m = 1, 2, \dots$  equation (1) becomes:

$$\begin{aligned} & \left[ \frac{(a_x - X_1)}{A_1} - \frac{(a_x - X_2)}{A_2} \right] X + \left[ \frac{(a_y - Y_1)}{A_1} - \frac{(a_y - Y_2)}{A_2} \right] Y = \\ & \Delta T_{12}V - A_1 + A_2 + \frac{(a_x - X_1)a_x}{A_1} + \frac{(a_y - Y_1)a_y}{A_1} - \frac{(a_x - X_2)a_x}{A_2} - \frac{(a_y - Y_2)a_y}{A_2} \end{aligned} \quad (5)$$

Equation (2) expanded in a similar way and combined with equation (1) results in two equations and two unknowns in linear form, solvable by Cramer's rule. By defining:

$$\frac{a_q - Q_m}{A_m} = Q_{pm}, \quad (6)$$



where Q may be X or Y and q may be x or y, and

$$C_{mn} = -A_m + A_n + a_x X_{mn} + a_y Y_{mn} - a_x X_{nn} - a_y Y_{nn}, \quad (7)$$

then the two equations and two unknowns become:

$$(X_{11} - X_{22})X + (Y_{11} - Y_{22})Y = \Delta T_{12}V + C_{12} \quad (8)$$

$$(X_{33} - X_{44})X + (Y_{33} - Y_{44})Y = \Delta T_{34}V + C_{34}. \quad (9)$$

The solution to these pseudo equations does not assure an accurate solution because of the assumed position. An iterative technique improves the answer to any desired accuracy, where the resultant answers X, Y are used in place of  $a_x$ ,  $a_y$  and the whole process repeated. This iterative process is continued until the change in the solution between two iterations is less than some predesignated error. When the change in the solution meets this criterion, a valid solution is assured for P.

The use of many tried examples has shown that an accurate knowledge of  $a_x$ ,  $a_y$  is not critical. In fact, a reasonable knowledge in the proper quadrant position is normally sufficient; either, convergence occurs within a few iterations, or no solution occurs. If the choice of  $a_x$ ,  $a_y$  is out of the convergence area, the solutions diverge and eventually overflow the computer. The area where a convergence occurs is dependent upon many factors, but in general those conditions that cause accurate solutions, such as intersecting hyperbolic lines, widely spaced sensors, and small  $\Delta T$ , also allow a large deviation of the initial estimated position from the true position. Appendix A is an example of one such Fortran program using this mathematical technique, along with other logic to be discussed later.

The forementioned method of solution is not the only possible one. Another method, which allows an exact solution by the solution of three equations, and three unknowns, can be derived by referencing figure 1 and noting that:

$$(X - X_1)^2 + (Y - Y_1)^2 = V^2 (T_1 - T_0)^2, \quad (10)$$

$$(X - X_2)^2 + (Y - Y_2)^2 = V^2 (T_2 - T_0)^2, \text{ and} \quad (11)$$

$$(X - X_3)^2 + (Y - Y_3)^2 = V^2 (T_3 - T_0)^2, \quad (12)$$

where the variables to be determined are X, Y, and  $T_0$ ;  $T_0$  being the initial time of sound output. By expanding equations (10), (11), and (12), and subtracting equation (11) from (10):

$$T_0 (V^2 T_1 - V_1^2 T_2) + X(X_2 - X_1) + Y(Y_2 - Y_1) = [X_2^2 + Y_2^2 - X_1^2 - Y_1^2 + V^2 (T_1^2 - T_2^2)]/2 \quad (15)$$

Likewise, subtracting equation (12) from (10):

$$T_0(V^2T_1 - V^2T_3) + X(X_3 - X_1) + Y(Y_3 - Y_1) = [X_3^2 + Y_3^2 - X_1^2 - Y_1^2 + V^2(T_1^2 - T_3^2)]/2. \quad (14)$$

And subtracting equation ~~(11)~~<sup>(12)</sup> from ~~(10)~~<sup>(11)</sup>:

$$T_0(V^2T_3 - V^2T_2) + X(X_2 - X_3) + Y(Y_2 - Y_3) = [X_2^2 + Y_2^2 - X_3^2 - Y_3^2 + V^2(T_2^2 - T_3^2)]/2. \quad (15)$$

Equations (13), (14), and (15) now allow X, Y, and  $T_0$  to be solved, with  $T_0$  not necessarily being needed for solution. One disadvantage to this method is the lack of an answer when solution redundancy exists. An example is when the sensors are in a nearly straight line, the possibility now exists that two solutions are available for the same input parameters. This appears as an indeterminacy, a problem that does not exist in the previously mentioned method when the start positions can be made to favor one of the solutions.

## ERROR CONSIDERATIONS

The location error due to the iterative technique can be reduced to a desired value by changing the error criteria, but errors also occur from three other conditions:

### 1. Velocity Error

The velocity error occurs when wrong V information is used to solve the hyperbolic solution. The V error is not too significant when the  $\Delta T$ 's between sensors are small, but an exception is when the effective V to the different sensors varies because of propagation effects. The section entitled VELOCITY DETERMINATION BY SELF COMPENSATION TECHNIQUES (page 9) describes a method of calculating the effective V to overcome some of these anomalies.

### 2. Time Measurement Error

Time measurement error is a mechanical error dependent upon the ability to determine, with equal criteria, the arrival of the sound source at the sensors. Classically for impulsive sound sources, such as artillery, the leading portion of the acoustical wavefront is used as a reference from which T is measured, though the definitiveness of two corresponding wavefronts at different sensor locations can become unclear, especially when long propagation paths are involved. Techniques, such as filtering and cross correlation, are methods by which trained human operators and electronic logic can reduce this error, though V error due to different propagation paths to the sensors can complicate time of arrival decisions.

### 3. Sensor Mislocation Error

Error due to sensor position errors can result in location error, depending upon the degree of sensor mislocation and geometry. Fortunately, there is some relief for this error by at least two techniques. One is the calibration of the sensor location by using calibrating shots, as discussed in the section entitled SENSOR LOCATION CALIBRATION EQUATION (page 6). Another technique, which allows for all the forementioned errors to be minimized, is the use of a sound-on-sound technique. Here, advantage is taken of the fact that, even though there is a sensor location error between the real location of the sound source and the apparent (calculated) position due to sensor mislocation, this position error tends to be invariant for any other sound source located in the same area. Operationally this allows the apparent sound source and the apparent source of the explosion of the return gunfire to be noted with some assurance that the vector correction for the next return shot being closer. This sound-on-sound technique allows for all types of index errors, including velocity errors, as long as the errors are invariant.

Appendix B gives an example solution of this sound-on-sound technique using the program listed in appendix A.

### S O R T I N G    T E C H N I Q U E S    F O R    U S E W I T H    C O N F U S E D    I N P U T S

Operationally, the problem of sound source location is complicated when more than one sound is received at a sensor within a short time frame and no prior information exists on which sound belongs to the target of interest. Such action can be caused by the presence of more than one sound source firing within a short time frame, from a single gun with multiple path transmission, reverberation or the presence of a shock wave from the projectile itself, and background sounds.

One computational method, which reduces appreciably the resultant confusion from this array of data, is to take advantage of the invariance of the solution with sensor position for shot combinations from the same source as opposed to the variation in the solution for combinations of different shots.

As an example, with  $P_1, P_2, P_3, P_4$  being four sensors and  $P_a, P_b$  being two guns (figure 2), the guns explode at about the same time, which will basically have all sensors receiving two echoes (unless the timing and geometry have some of the shots superimposed). From the possible combination of echoes, any three sensors, such as  $P_1, P_2$ , and  $P_3$ , will have eight possible solutions, and any other three sensors, such as  $P_2, P_3, P_4$ , will also have eight solutions. In general, only two solutions exist from the first solutions, which will find an identical mate in the second set of solutions, these being positions  $P_a$  and  $P_b$ . It is possible that other matings can occur, but the geometry and timing to be, by coincidence,

just right. This coincidence mating anomaly can be minimized even more so by extending the technique to one more unique set of solution sensors, where complete mating must incur among the three sets of eight solutions. This sorting technique has proven successful; a simulated example of its use is shown in appendix C using the program listed in appendix A.

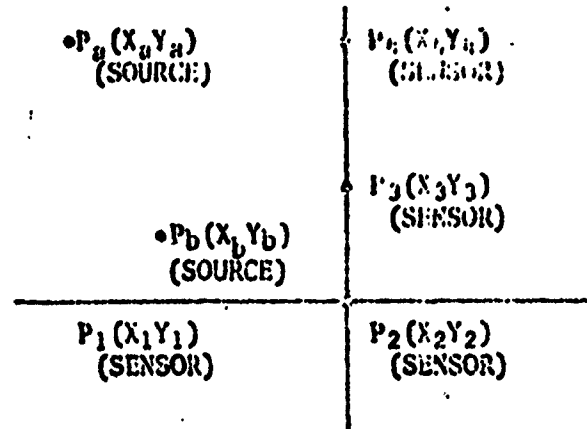


FIGURE 2

# SENSOR LOCATION CALIBRATION EQUATION

It is desirable to calibrate the location of sensor pairs by using the knowledge of the location of a series of sound sources and their times of arrival at the sensors. This is the complementary problem discussed in the section entitled DERIVATION OF SOURCE LOCATION EQUATION (page 1), where one might want to calibrate the sensor location so that errors in using these sensors for sound location purposes is minimized. With the similar hypothesis that only the time differences between sensors and the sound sources locations are known, figure 3, one can rewrite equation (1) as:

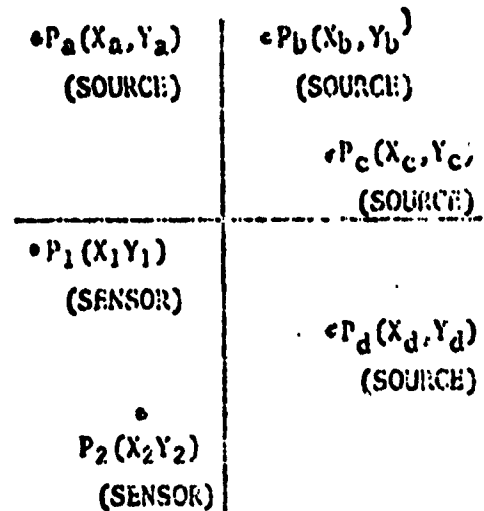


FIGURE 3

$$[(X_a - X_1)^2 + (Y_a - Y_1)^2]^{1/2} - [(X_a - X_2)^2 + (Y_a - Y_2)^2]^{1/2}$$

$$= \Delta T_{a12} V, \quad (16)$$

where  $X_1, Y_1$ ,  $X_2, Y_2$  are the coordinates of any two unknown sensors,  $X_a, Y_a$  is a known source, and  $\Delta T_{a12}$  is the time difference between sensor  $P_1$  and sensor  $P_2$  of a sound from source  $P_a$ .

Since four variables must be resolved at a time, four simultaneous independent equations must be solved. This is achieved by noting the time of arrivals from four different sound sources, or in this case three more equations like equation (16) are written using  $P_b$ ,  $P_c$ , and  $P_d$  in place of  $P_a$ .

Here again arises the problem of nonlinear simultaneous equations, and Taylor's series expansion are used for solution.

The beginning terms of the Taylor's expansion of the relationship  $[(X_a - X_1)^2 + (Y_a - Y_1)^2]^{1/2}$  about a point  $q_1, r_1$  for  $X_1, Y_1$  results in:

$$F(X_1, Y_1) = F(q_1, r_1) + \left. \frac{\partial F}{\partial X_1} \right|_{q_1, r_1} (X_1 - q_1) + \left. \frac{\partial F}{\partial Y_1} \right|_{q_1, r_1} (Y_1 - r_1) \quad (17)$$

$$\begin{aligned} \text{or } [(X_a - X_1)^2 + (Y_a - Y_1)^2]^{1/2} &\approx [(X_a - q_1)^2 + (Y_a - r_1)^2]^{1/2} \\ &+ (X_a - q_1)(X_1 - q_1)[(X_a - q_1)^2 + (Y_a - r_1)^2]^{-1/2} \\ &+ (Y_a - r_1)(Y_1 - r_1)[(X_a - q_1)^2 + (Y_a - r_1)^2]^{-1/2} \end{aligned} \quad (18)$$

Similarly by defining  $A_{an} = [(X_n - q_n)^2 + (Y_n - r_n)^2]^{1/2}$  and expanding  $X_2, Y_2$  about a point  $q_2, r_2$  results in equation (16) becoming:

$$\begin{aligned} &\frac{[(X_a - q_1)(X_1 - q_1) + (Y_a - r_1)(Y_1 - r_1)]}{A_{a1}} \\ &- \frac{[(X_a - q_2)(X_2 - q_2) + (Y_a - r_2)(Y_2 - r_2)]}{A_{a2}} = A_{a2} - A_{a1} + \Delta T_{a12}V; \end{aligned} \quad (19)$$

or in more conventional form, as:

$$\begin{aligned} &\frac{(X_a - q_1)X_1}{A_{a1}} + \frac{(Y_a - r_1)Y_1}{A_{a1}} - \frac{(X_a - q_2)X_2}{A_{a2}} - \frac{(Y_a - r_2)Y_2}{A_{a2}} \\ &= \Delta T_{a12}V + C_{a12}, \end{aligned} \quad (20)$$

where

$$\begin{aligned} C_{a12} = A_{a2} - A_{a1} &+ \frac{q_1(X_a - q_1)}{A_{a1}} + \frac{r_1(Y_a - r_1)}{A_{a1}} - \frac{q_2(X_a - q_2)}{A_{a2}} \\ &- \frac{r_2(Y_a - r_2)}{A_{a2}}. \end{aligned} \quad (21)$$

By a similar development for sound sources  $P_b$ ,  $P_c$ , and  $P_d$ , the four simultaneous equations become:

$$\frac{(x_a - q_1)x_1}{A_{a1}} + \frac{(y_a - r_1)y_1}{A_{a1}} - \frac{(x_a - q_2)x_2}{A_{a2}} - \frac{(y_a - r_2)y_2}{A_{a2}} = \Delta T_{a12}V + C_{a12}, \quad (22)$$

$$\frac{(x_b - q_1)x_1}{A_{b1}} + \frac{(y_b - r_1)y_1}{A_{b1}} - \frac{(x_b - q_2)x_2}{A_{b2}} - \frac{(y_b - r_2)y_2}{A_{b2}} = \Delta T_{b12}V + C_{b12}, \quad (23)$$

$$\frac{(x_c - q_1)x_1}{A_{c1}} + \frac{(y_c - r_1)y_1}{A_{c1}} - \frac{(x_c - q_2)x_2}{A_{c2}} - \frac{(y_c - r_2)y_2}{A_{c2}} = \Delta T_{c12}V + C_{c12}, \quad (24)$$

$$\frac{(x_d - q_1)x_1}{A_{d1}} + \frac{(y_d - r_1)y_1}{A_{d1}} - \frac{(x_d - q_2)x_2}{A_{d2}} - \frac{(y_d - r_2)y_2}{A_{d2}} = \Delta T_{d12}V + C_{d12}. \quad (25)$$

These equations can be solved by Cramer's rule, the resultant  $x_1$ ,  $y_1$ ,  $x_2$ , and  $y_2$  used as the  $q_1$ ,  $r_1$ ,  $q_2$ , and  $r_2$  in an iterative process until consecutive  $x_1$ 's,  $y_1$ 's,  $x_2$ 's, and  $y_2$ 's are less, with a defined difference of each other. Convergence is readily obtainable even with large errors of input positions, though care must be taken to insure that four independent equations result from the choice of sound location positions. Normally preventing symmetry of location positions will insure this independency.

# VELOCITY DETERMINATION BY SELF COMPENSATION TECHNIQUES

One of the operational considerations that can affect the accuracy of sound source location is the use of an improper velocity parameter. Velocity in air is dependent upon humidity, temperature, barometric pressure, and amplitude of the sound source pressure. These errors are compounded by spatial variation with horizontal and vertical gradients, causing unusual sound propagation paths. By use of a comparative technique, it is possible to derive a relationship for an effective velocity which can be used in the basic equation of location as discussed in the first section (page 1).

To derive such a relationship, advantage is taken of the fact that two unique solutions of the same sound source location must coincide; i.e., if the sensor locations are accurate and if it can be assured that the times of arrivals at the different sensors are from the same source, then the resulting positions agree. As an example (figure 4), the solution of P, using information from P<sub>1</sub>, P<sub>2</sub>, and P<sub>3</sub>, must equal that from P<sub>1</sub>, P<sub>2</sub>, and P<sub>4</sub>, both in X and in Y. In actuality, a close approximation to this requirement can be made by using the iterative techniques mentioned in the first section (page 1).

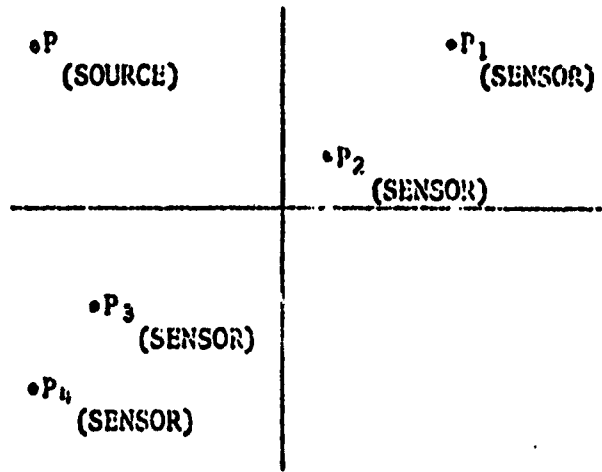


FIGURE 4

Using equations (1) through (9) as bases, defining:

$$A_m = [(a_x - x_m)^2 + (a_y - y_m)^2]^{1/2} \quad (26)$$

$$C_{mn} = -A_m - A_n + a_x x_{nm} + a_y y_{nm} - a_x x_{nm} - a_y y_{nm} \quad (27)$$

$$A_{nn} = [(x_m - q_n)^2 + (y_m - r_n)^2]^{1/2} \quad (28)$$

$$Q_{mn} = \frac{a_q - Q_m}{A_m}, \quad Q \text{ being either } X \text{ or } Y. \quad (29)$$

The approximate solution for X, using sensors P<sub>1</sub>, P<sub>2</sub>, and P<sub>3</sub>, with P<sub>2</sub> being common, becomes:

$$X_{123} = \frac{\begin{vmatrix} \Delta T_{12}V + C_{12} & Y_{11} - Y_{22} \\ \Delta T_{23}V + C_{23} & Y_{22} - Y_{33} \end{vmatrix}}{\begin{vmatrix} X_{11} - X_{22} & Y_{11} - Y_{22} \\ X_{22} - X_{33} & Y_{22} - Y_{33} \end{vmatrix}} \quad (30)$$

This solution to X is dependent upon the accuracy of  $a_x$ ,  $a_y$ , the start positions, but is actually not too critical for the purpose of velocity determination. By the same token:

$$X_{124} = \frac{\begin{vmatrix} \Delta T_{12}V + C_{12} & Y_{11} - Y_{22} \\ \Delta T_{24}V + C_{24} & Y_{22} - Y_{44} \end{vmatrix}}{\begin{vmatrix} X_{11} - X_{22} & Y_{11} - Y_{22} \\ X_{22} - X_{44} & Y_{22} - Y_{44} \end{vmatrix}} \quad (31)$$

Equating equations (30) and (31) and defining:

$$\begin{vmatrix} X_{11} - X_{22} & Y_{11} - Y_{22} \\ X_{22} - X_{33} & Y_{22} - Y_{33} \end{vmatrix} = Z_{123}, \text{ and} \quad (32)$$

$$\begin{vmatrix} X_{11} - X_{22} & Y_{11} - Y_{22} \\ X_{22} - X_{44} & Y_{22} - Y_{44} \end{vmatrix} = Z_{124} \quad (33)$$

one obtains:

$$\begin{aligned} & [(\Delta T_{12}V + C_{12})(Y_{22} - Y_{44}) - (\Delta T_{24}V + C_{24})(Y_{11} - Y_{22})]Z_{123} \\ & = [(\Delta T_{12}V + C_{12})(Y_{22} - Y_{33}) - (\Delta T_{23}V + C_{23})(Y_{11} - Y_{22})]Z_{124} \end{aligned} \quad (34)$$

By separating the velocity term and defining:



$$G = Z_{124}[C_{12}(Y_{22} - Y_{33}) - C_{23}(Y_{11} - Y_{22})] \\ - Z_{123}[C_{12}(Y_{22} - Y_{44}) - C_{24}(Y_{11} - Y_{22})] \quad (35)$$

$$H = Z_{123}[\Delta T_{12}(Y_{22} - Y_{44}) - \Delta T_{24}(Y_{11} - Y_{22})] \\ - Z_{124}[\Delta T_{24}(Y_{22} - Y_{33}) - \Delta T_{23}(Y_{11} - Y_{22})] \quad (36)$$

then:

$$V = G/H. \quad (37)$$

One is not always assured that a solution for V can be obtained this way. Ideal geometry of a problem, such as having the sound source located close to the perpendicular bisectors of the sensor orientations (near zero time difference to the sensors), results in a nearly indeterminate value for these equations. This becomes apparent by the near zero value of the denominator of these equations. If this happens with X being essentially invariant on velocity, then the complementary equations on Y should be used. If a similar indeterminacy occurs when the complementary equations are used, then the parameters tending to make this velocity determination difficult are the same as those that make the location problem insensitive to velocity.

Though the academic approach of this procedure is quite straightforward, certain practical cares must be taken before such a scheme of velocity solution is used. Paramount is the assurance that the positions being matched are truly from the same source. Even in the presence of multiple input data, the use of range gates and assurance of time redundancy for two sensors should normally assure the validity of the approach.

When additional error is imposed by such factors as improper sensor location knowledge, this velocity correction technique still forces a solution that marries the positions. Using arguments similar to that mentioned in the section entitled ERROR CONSIDERATIONS (page 4), this velocity correction technique is now a whole system correction factor, allowing fire and counterfire vector corrections to be effective even though there is an absolute calibration error. The combination of velocity correction and sorting techniques into one program could prove to be an effective way of solving a fire control problem operationally. Appendix A lists this velocity subroutine as part of the basic program for sound location.

Finally this same type of velocity concept can be used for the complementary problem of sensor field location. By using equations (22) thru (25) and solving for  $X_1$  twice, once when sensor  $P_2$  is used and once when a different sensor  $P_3$  is used, then equating the  $X_1$ 's together, one can derive a solution for velocity. By defining:

$$M_{mn} = \frac{M_m - f_n}{A_{mn}} \quad (M \text{ being either } X \text{ or } Y), \quad \begin{matrix} f = x \text{ when } M = X \\ f = y \text{ when } M = Y \end{matrix} \quad (38)$$

and  $q_3, r_3$  are start positions for  $P_3$  and

$$W_r = \begin{vmatrix} Y_{a1} - X_{ar} + Y_{ar} \\ Y_{b1} - X_{br} + Y_{br} \\ Y_{c1} - X_{cr} + Y_{cr} \\ Y_{d1} - X_{dr} + Y_{dr} \end{vmatrix} \quad (39)$$

and

$$\bar{Z}_{ar} = \begin{vmatrix} Y_{b1} - X_{br} + Y_{br} \\ Y_{c1} - X_{cr} + Y_{cr} \\ Y_{d1} - X_{dr} + Y_{dr} \end{vmatrix} \quad (40)$$

and

$$Z_q = \begin{vmatrix} X_{a1} - Y_{a1} + X_{aq} - Y_{aq} \\ X_{b1} - Y_{b1} + X_{bq} - Y_{bq} \\ X_{c1} - Y_{c1} + X_{cq} - Y_{cq} \\ X_{d1} - Y_{d1} + X_{dq} - Y_{dq} \end{vmatrix} \quad (41)$$

Then by using  $X$  as a match between sensor pairs  $P$  and  $P$ , and  $P$  and  $P$ :

$$X_1 = \begin{vmatrix} \Delta T_{a12}V + C_{a12} \\ \Delta T_{b12}V + C_{b12} \\ \Delta T_{c12}V + C_{c12} \\ \Delta T_{d12}V + C_{d12} \end{vmatrix} \begin{bmatrix} W_2 \end{bmatrix} = \begin{vmatrix} \Delta T_{a13}V + C_{a13} \\ \Delta T_{b13}V + C_{b13} \\ \Delta T_{c13}V + C_{c13} \\ \Delta T_{d13}V + C_{d13} \end{vmatrix} \begin{bmatrix} W_3 \end{bmatrix} \quad (42)$$


---

$Z_2$

$Z_3$

or defining:

$$\begin{aligned} & Z_3(\Delta T_{a12}Z_{\bar{a}2} - \Delta T_{b12}Z_{\bar{b}2} + \Delta T_{c12}Z_{\bar{c}2} - \Delta T_{d12}Z_{\bar{d}2}) \\ & - Z_2(\Delta T_{a13}Z_{\bar{a}3} - \Delta T_{b13}Z_{\bar{b}3} + \Delta T_{c13}Z_{\bar{c}3} - \Delta T_{d13}Z_{\bar{d}3}) = G \end{aligned} \quad (43)$$

and

$$\begin{aligned} & Z_2(C_{a13}Z_{\bar{a}3} - C_{b13}Z_{\bar{b}3} + C_{c13}Z_{\bar{c}3} - C_{d13}Z_{\bar{d}3}) \\ & - Z_3(C_{a12}Z_{\bar{a}2} - C_{b12}Z_{\bar{b}2} + C_{c12}Z_{\bar{c}2} - C_{d12}Z_{\bar{d}2}) = H \end{aligned} \quad (44)$$

$$\text{then } V = H/G. \quad (45)$$

The same comments mentioned earlier pertain to this method of self correction of velocity, such as assumed uniform velocity to all sensors from all sources.

NADC-80040-40

APPENDIX L

Excerpts from A Sensor System  
For Artillery Location, NADC-72180-SD

## BACKGROUND OF ANNIE OAKLEY

During May of 1972, emergency funds were released for the purpose of expediting the development of an experimental acoustical artillery location system for possible use in SEA (Southeast Asia); enclosures (1) and (2) specifically relate to this tasking. The particular proposed acoustical artillery location under investigation, called "ANNIE OAKLEY," was closely related to existing acoustical gun location systems, such as the Army's GR-8, but this proposal had several features designed to improve operational usefulness. Nonreliance on hardwired sensors, computer software techniques which tend to reduce the CEP (circular error of probability) of gun location while simultaneously reducing the false alarms, and a design philosophy which wholly automates the gun location process were specific improvements over existing systems. Figure 1 is a block diagram of the envisioned system operating through an r-f link.

The concept had been under investigation since late 1967 with original support coming from DDR&E (Director of Defense Research and Engineering) and ARPA (Advanced Research Projects Agency). The original effort was not operationally useful - mainly due to the lack of development effort on the concept - but follow-on analytical efforts by the Navy revealed sufficient promise to permit continued support from the Army. In this effort, NAVAIRDEVCECEN served as a technical monitor of JHU/APL (Johns Hopkins University/Applied Physics Laboratory) and Analytics Corporation for the USAECOM (U. S. Army Electronics Command). This program was essentially completed in August 1972, and at the present time a final summary report is forthcoming from NAVAIRDEVCECEN. A summary of pertinent reports, to date of this Army oriented and supported program, is as follows:

1. A complete cataloguing of test data taken of analogue magnetic recordings during Fort Sill, Oklahoma tests in the summer of 1969. These tests, originally designed to evaluate the performance of existing gun location systems for a variety of guns operating in various modes of operation, had many instrumented quality microphones placed over the operating area at Fort Sill, Oklahoma and their outputs tape recorded. These recordings, and the associated cataloguing, served as a test data base for analysis purposes and validation of experimental systems.

2. Four reports published by NAVAIRDEVCECEN, references (a), (b), (c), and (d) which as an aggregate summarizes into the following:

- a. Validation of the above mentioned test tapes concerning their usefulness.

- b. Actual testing of the analogue data in a laboratory version of an automated, but limited area coverage, computerized gun location system. Different subroutines were experimentally tested to evaluate the feasibility of operating in a high data rate with low false alarms, high probability of detection, and satisfactory CEP's.

- c. Analytical studies related to methods of determining a measure of system effectiveness, and software methods of improving fixing accuracy and reducing computer loading.

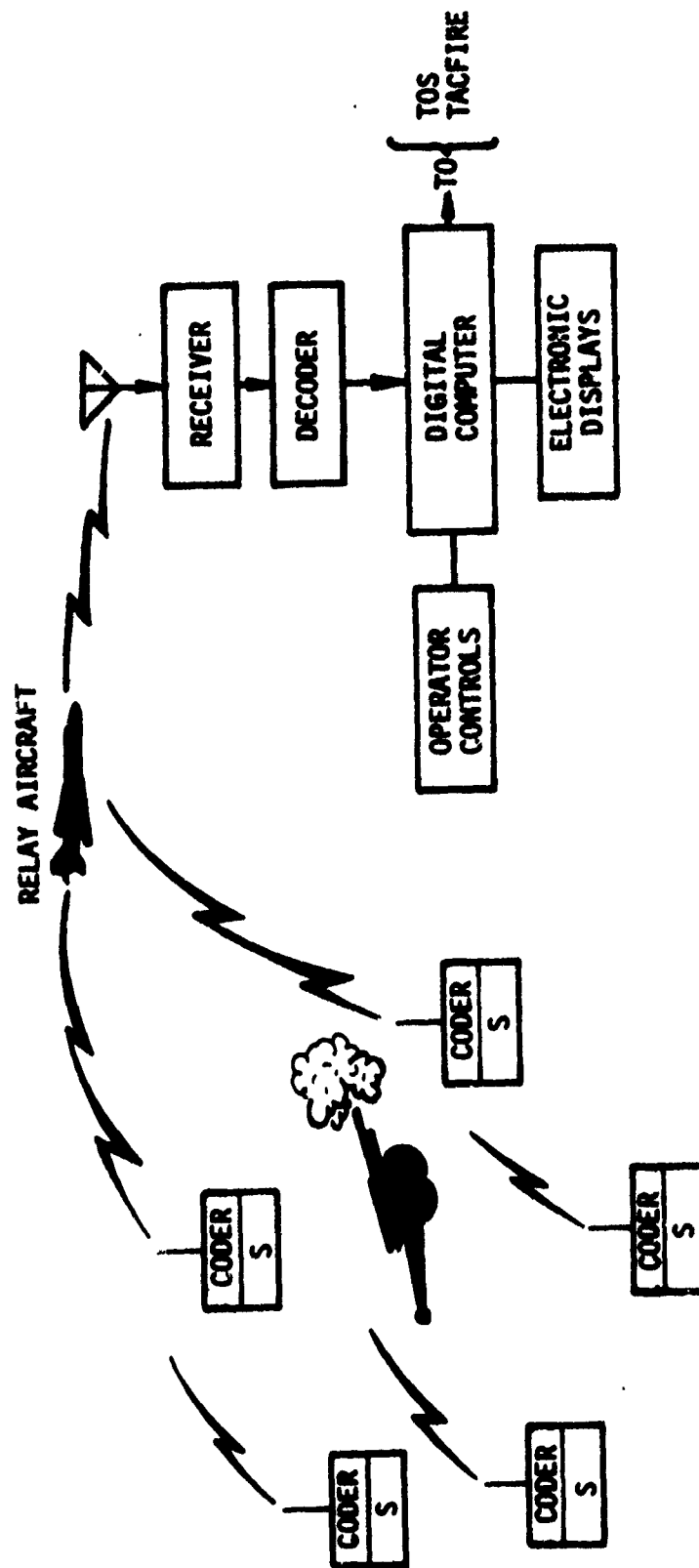


FIGURE 1 - Block Diagram of ANNIE OAKLEY System

d. Volume III - Technical Report. Related studies including accuracies expected and tradeoffs for computer operation.

4. The demonstration at JHU/APL on 6 August 1972 of a large scale simulated system (on an IBM 360-91 computer) using both recorded Fort Sill data and simulated sensor inputs. The demonstration validated the feasibility of such advanced concepts as automated MET (meteorological) and sensor registration along with the simultaneous operation of a large sensor (50 sensor) field. Reference (i) is a summary of that demonstration.

The program had three basic development efforts: (1) the development and definition of the sensor to be used, (2) the development of some form of operational scenario which the system was to work within and, (3) development of the basic hardware/software computer system which would process the sensor information. Because of the short development time allowed, the program had the following initial constraints/guidance as to technical direction:

1. Only existing acoustical activated DSPG (Defense Special Projects Group) sensors, or minor modification heretofore, would be acceptable. Previous efforts of the Army's "ANNIE OAKLEY" program revealed the desirability of designing a sensor with classification within the sensor, but at least six months development time was required for sufficient circuit design maturity to even approach operational (SEA) use.

2. Only minor modifications from the computerized laboratory system at NAVAIRDEVCEEN could be done within the time constraints with reasonable risk, and then only a computer system which was similar to the laboratory system. In addition, one which was MILSPEC and supportable, both software and hardware was desired. Further improvements in software were considered acceptable at a later date as they became available.

3. No impact on the existing software program at NKP could be tolerated.

4. The actual computer program at NKP was not identical to that used at Eglin AFB, and documentation as to its exact contents was difficult to obtain.

5. Operationally, the previous acoustical artillery philosophies and scenarios of the Army would serve as basic guides (i.e., the analyses contained in references (e) through (h) and the QMR/QMDO's (Qualitative Materiel Requirement/Qualitative Materiel Development Objective) on artillery location, reference (j), (k), being the basic requirements documents). Fundamentally, these scenarios required a "real-time" operational system where answers for a return fire situation should result in less than 1 minute after a gun was fired with accuracy between 35 to 200 meters. Enclosure (3) summarizes the faults of present operational gun location systems, along with excerpts from the field manual on the organization and operation of a sound platoon.

6. If the concept was successfully proven in CONUS, the Navy would assist the Air Force in SEA for training purposes.

Personnel from both the Air Force and Navy visited NKP and MACV (Military Assistance Command Vietnam) personnel during late June. A redefinition of the operational environment revealed that only a Phase III sensor in a threshold mode could be operationally exploited by the Air Force at NKP; the use of raw acoustical data transmitted was not operationally desirable due to the very heavy demands this would place upon the existing r-f channels available in SEA. Enclosure (4) is the operational scenario which was used to assist in defining the operational use of a gun location device, while enclosure (5), a rough summary report of the SEA visit, reflects the desires and concerns of the operational personnel at SEA. The net result of these dialogues between MACV/CONUS personnel were as follows:

1. The strong desire for an operational system considerably more advanced than originally envisioned (i.e., more simultaneous area coverage and higher firing rate capability).
2. The urgency in SEA was tentatively reduced (i.e., the demonstration in CONUS could be delayed until September).

The net result was an increased sophistication of computer software/hardware, tested under controlled conditions at Eglin AFB on 7 September with the concept to be demonstrated to MACV, DDR&E and tri-service personnel on 28 September. Three different systems were tested - one airborne version and two ground versions; all of which were originally developed in parallel at various levels of risk to give the greatest assurance of the most meaningful success on the original planned CONUS test date of 17 August. All systems tested worked as designed with a nominal performance capability of a CEP for grouping purpose of less than 20 meters, an average location bias error of less than 100 meters when sensors were known within a distance of 100 meters, and POD (probability of detection) of about 80 percent in a firing environment where the sensors triggered individually at a rate of once every 6 seconds. At a higher trigger rate, the 7 September test approached conditions of average sensor trigger rate of once every two seconds, the sensor deactivation circuitry (3/4 second after threshold is exceeded) along with increased computer loading caused the POD to drop to about 30 percent. The modified Phase III sensor gave, detection ranges out to 11 km for the 81 mm mortar and the 105 and 155 mm artillery pieces. Subsequent tests reveal that even though thunder, aircraft flyover, and small arms fire do trigger the sensors - as a whole system the performance was not grossly affected. This was mainly due to the computer software logic against false alarms. In summary, the concept and systems performed equal to or greater than originally planned for at the beginning of the emergency funded effort.



## PRODUCT DESCRIPTIONS

During the prosecution of the program, many original hardware and computer software efforts resulted:

Modification to the Phase III Sensor for Impulse Operation

After tests at both Eglin and Quantico, which included a verification of original efforts in the Army's ANNIE OAKLEY Program, a satisfactory modification to the presently operational Phase III COMMIKE sensor was found. This modification essentially consisted of adding two circuit boards to the present COMMIKE package allowing an AGC of approximately 50 db/second, and a threshold circuit which would give a command transmit of the sensor ID if a signal strength of 15 db was exceeded. In addition, the input bandpass of the system was modified to go from 150 to 450 Hz. This setting gave the best all around results for the variety of guns and weather conditions which were experienced. Initially a lower frequency range, 10 to 50 Hz, was tried - but sensitivity to the wind noise gave unsatisfactory false alarms. As reported earlier, detection ranges over 11 km were normally experienced with an aggregate detection capability of the field in a slow fire situation (less than once every 10 seconds) being 92 percent. Figure 2 represents the detection capability of the sensor as a function of gun type and range. One factor noted was that even at short ranges, with known reliable sensors, the assurance that a sensor activation will not occur is finite ( 10 percent) and must be taken into account with the overall system design.

Weather conditions of winds from 6 to 15 knots, some light rain, and man-made noises were experienced. A false alarm average of less than one-a-minute per sensor occurred during the test, which proved to be most operationally acceptable for the tested hardware/software computer system. As reported in earlier Army studies, the need for classification within the sensor to differentiate muzzle, impact, and ballistic shots is most desirable, especially if a much higher firing rate is to be handled. During tests at Eglin and Quantico in June through August, supplementary acoustical recordings were also obtained to allow verification of earlier studies as to the possibility of designing a successful classification module for the three basic types of artillery induced noises (muzzle, ballistic, and impact sound).

During the many sensor design tests, modified seismic detectors and Phase II audio sensors were used for control. The Phase II sensor in the impulsive mode gave approximately one-half the detection range of the final modified Phase III sensor while the seismic sensor, apparently operating in a ground/air coupled mode, performed poorly (poor detection ranges); even though tested at a variety of sensor sensitivities it did not even approach that of the Phase II sensor. Finally, the modified Phase III sensor was tested in a spiked version with the microphone approximately 1 ft above the ground. This sensor in the Eglin terrain gave similar results as to the normal ( 30 ft) hang up mode.

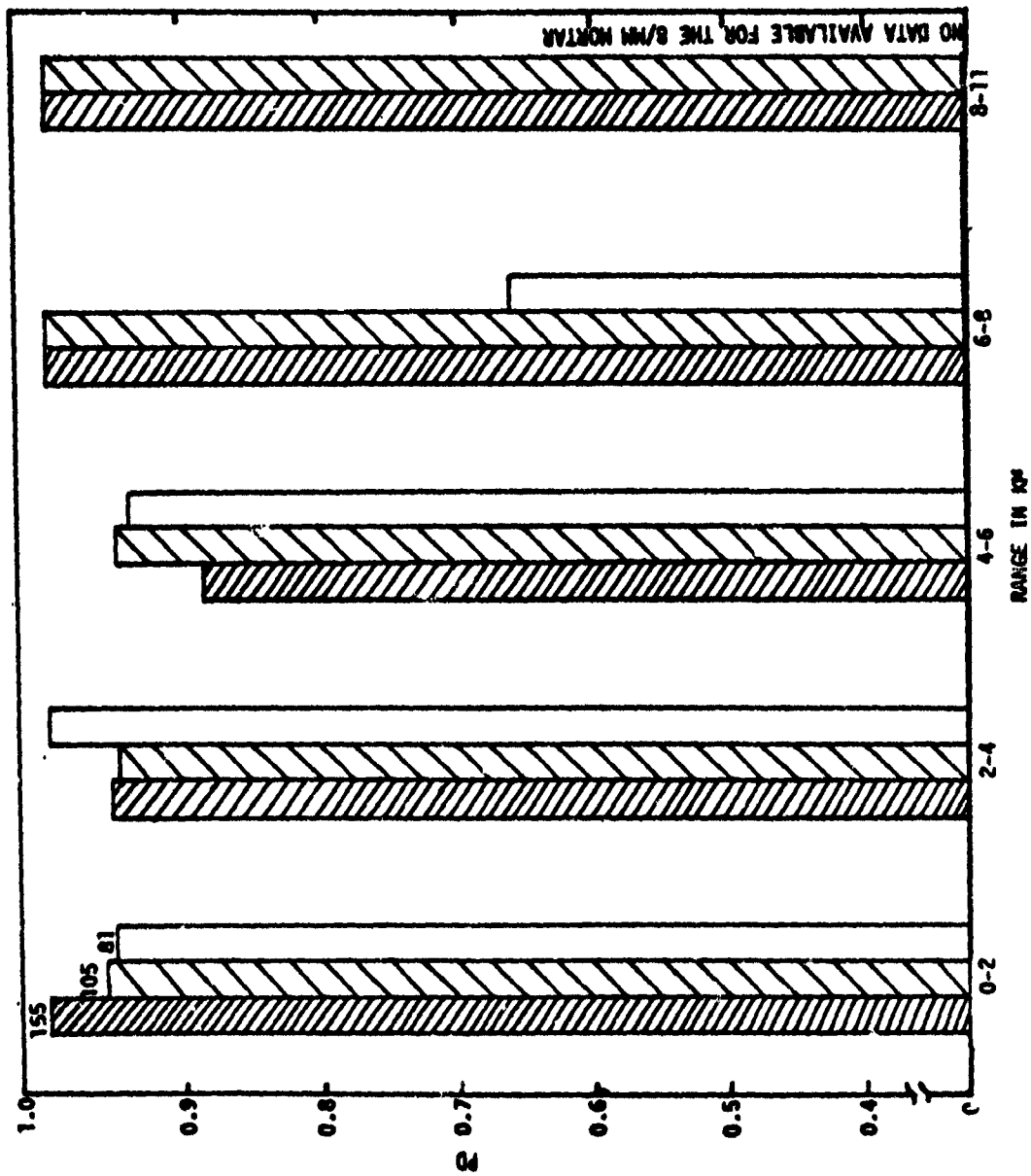


FIGURE 2 - Sensor Detections Versus Range

### Airborne Interface Hardware Equipment

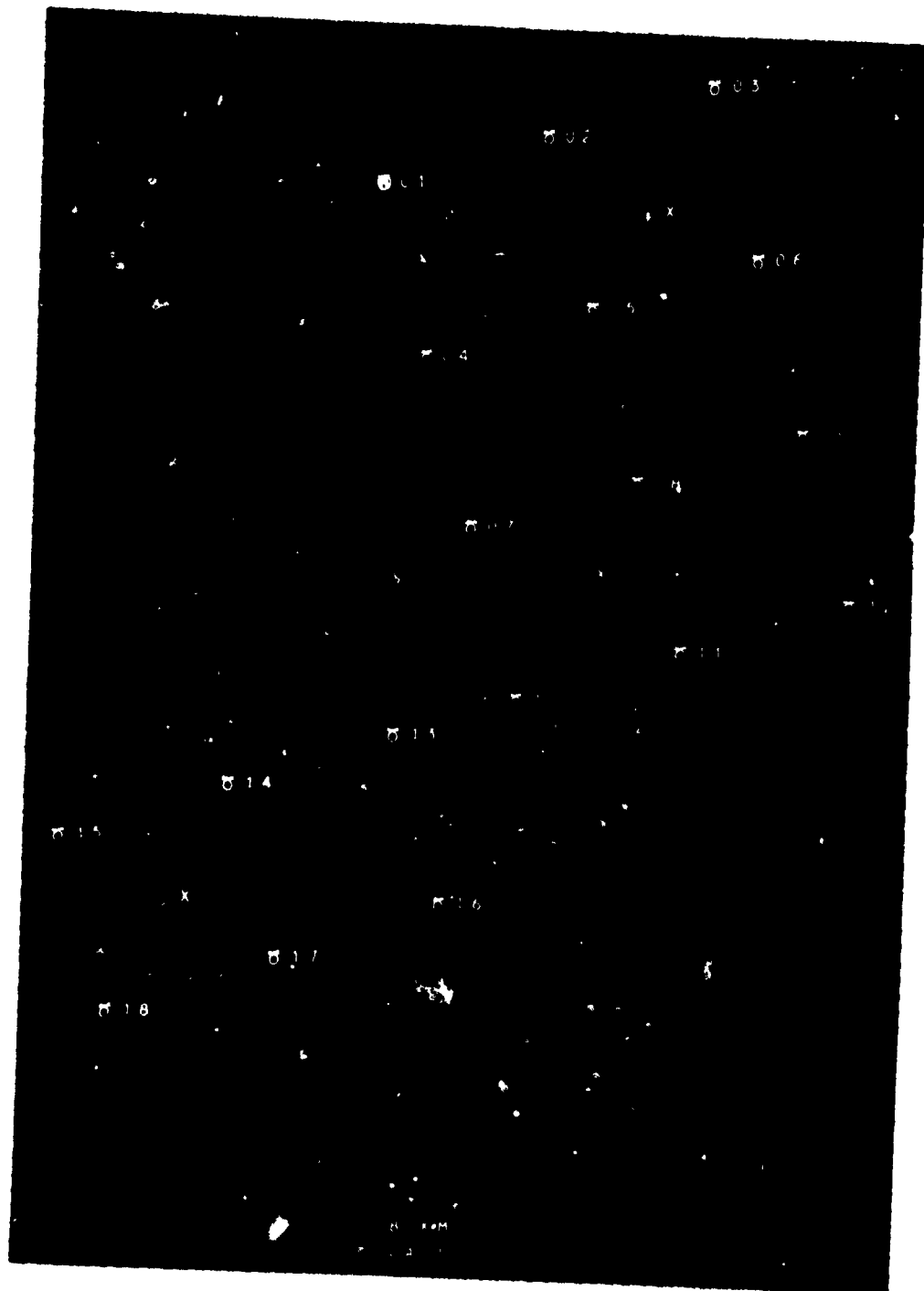
An airborne system with specialized hardware interface was designed to allow the adequate interfacing of the output of the sonobuoy receivers to the P3C computerized system. Though an airborne system was not a direct part of the primary tasking of this program, the ease in putting the existing laboratory computer software (the UNIVAC 1230 Laboratory Computer and the aircraft's 1830A Computer, of the same family, both using Navy Tactical Display System CS-1 software language) into the Navy's ASW patrol aircraft of the P3C, was most fortuitous. In conjunction with the necessary interface equipment used for recording of sensor data for analysis purposes, the ability to empirically evaluate the overall location system at the test sites without potential tape playback degradation was most valuable in finalizing the ground system design. Enclosure (6) is a block diagram of the aircraft system.

### Ground Station Interface Equipment

Approximately half way during the conduct of the program, it became evident that the best chance of final success of the program would occur if the hardware/software computer system was made essentially independent of the IBM 360/65 computer system in existence at Eglin and NKP. To assure proper operation, it becomes necessary to design both digital logic to give ID codes and auxiliary digital filtering to allow a more accurate presentation of ID information to the ANNIE OAKLEY Computer System in the presence of data loss. In addition to these two digital systems, there was designed logic to present pulses which would give a nominal 30 msec pulse to the computer system. This was done to ensure that a threshold signal would be seen by the gun location computer which sampled data at 10 msec. Enclosure (7) reflects the final block diagram of the interface equipment between the sensor receivers and the gun location computer system tested at Eglin. The system performed as designed and provided most adequate information to the gun location system.

### P3C Aircraft Computer ANNIE OAKLEY System

This system, primarily developed to allow early exposure of the gun location concept for testing on field data, consisted mainly of the basic program developed in the laboratory for testing purposes. This basic system had the capability of receiving up to 16 sensors to be monitored simultaneously, though only five were selected and used for fixing, with a sensor detection being displayed on a 14 in. cathode ray display tube. Figure 3 presents a typical sensor field presentation (used for the 7 September test) on the display where a detection is an X and the O's are the sensors. The program had a variety of laboratory oriented options including the use of a modified form of Taylor expansion to do the hyperbolic fixing or a mapping technique known as Conformal Mapping which will give a slightly degraded fixing accuracy but with much less computer loading. The real time requirement for all the computer systems was the major limiting factor. In addition, the aircraft system has a software option known as system velocity, a subroutine which tended to make final answers more accurate due to the automatic determination of sound velocity if only approximate values were known. A basic description of software of this system is contained as an enclosure to reference (a).



0 = SENSOR LOCATION

X = GUN LOCATION (FIX)

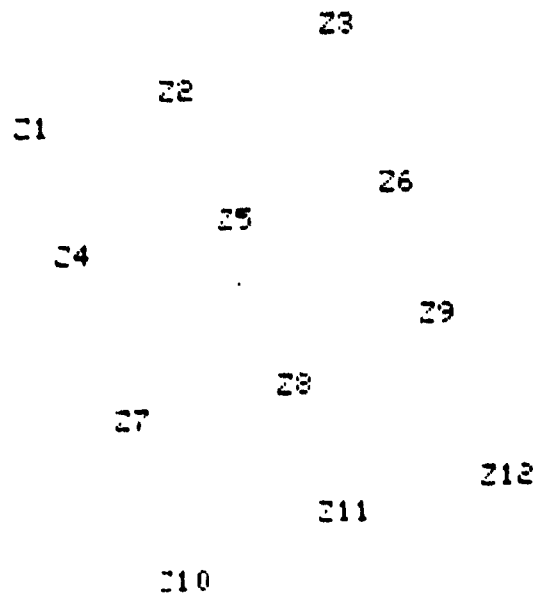
L-9

This airborne computer system, taking advantage of existing MILSPEC computers and displays, gave the earliest form of a gun location system. Though limited by existing software, it had the most flexible and powerful capability due to the basic capability of the P3C aircraft computer display system. Covering an area of nominally 10 or more square kilometers at a time, the results in accuracy and detection for similar area coverage was essentially the same as the other ground systems tested. Again, its major limitations being the lack of flexibility and area coverage and the requirement for human decision making. These were all solvable with software modifications as done for the higher priority ground systems.

#### Mainstream Ground ANNIE OAKLEY System

Since the beginning of the program, the basic design philosophy was to develop a ground base system which would tie into the existing NKP computer system. The gun location system hardware chosen was that using a UNIVAC 1616/UYK-15 computer system, a Hazeltine 2000 alphanumeric display, a Raytheon analog/digital converter, and associated peripheral equipments of two magnetic tape systems and keysets. These equipments were chosen mainly because of their availability and familiarity in similar type application at the NAVAIRDEVCON, the identical hardware equipment having been installed aboard the USS GUAM. Of equal importance was the computer system's supportability; the basic concern being standard computer language (essentially NTDS compatible) and MILSPEC, along with growth potential because the end product of the computer system was not yet defined. The UYK-15 is MILSPEC with a main frame capability of 65,000 words plus many options including a hardwired FFT module.

The system to be demonstrated on 28 September has a multiple display capability including TV, alphanumeric, and high-speed hard-copy printer, the latter giving fix coordinates and the calculated times the gun fires. In addition, by program interruption for about 20 seconds, a hard-copy printout of what is seen on the display at anytime can be had. The specific computer program, mainly a derivative of the laboratory system with improvements to allow up to four areas to be covered at one time, can use a total of up to 28 sensors for fixing (though 32 sensors can be displayed for the purpose of noting individual sensor activation rate). In addition, this program also has the ability to accept manual input to insert wind corrections. Finally, the display to this program is both the small alphanumeric display and a larger 23 in. TV display. Though the larger display is still not as flexible as compared to P3C display, improvements to it are expected within a few months allowing a greater presentation resolution (512 points versus 256), smaller character letters, and "hook" function which allows the display "hook" to talk directly to the computer without using the keyset. Figure 4 shows a typical presentation of the sensor field. Figure 5 shows the display in a communication mode with the ability to set up the latitude/longitude of the sensor fields centric. Enclosure (8) describes the program's function, control function, and serves as an operator's manual. Assistance in software support for this system and in the aircraft was given by the UNIVAC Corporation.



IMPULSIVE A. D.

SCALE 8 NM  
CATEGORY 0

FIGURE 4 - Impulsive ANNIE OAKLEY - Sensor Field  
L-11

## Developmental ANNIE OAKLEY System

In addition to the mainstream effort for ground based system, essentially minor modifications to the existing laboratory software philosophy, a backup system including hardware was developed where greater freedom was allowed in the nature of the software programming. Based on previous Army efforts, certain desirable features have been investigated and demonstrated to improve the overall performance of any gun location system. The philosophy behind the efforts of the backup system was to allow early investigation of the various computer programming techniques on a machine which, though limited in growth potential and MILSPEC supportability, was available at NAVAIRDEVCEEN and had Fortran programming capability for ease of program modifications. A separate support contractor (Analytics, Incorporated) who was familiar with the basic ANNIE OAKLEY program, was used for this program development to ensure no dilution of the mainstream computer efforts. In addition, JHU/APL personnel were used to support the total effort in program philosophy, based upon their long familiarity with the Army's ANNIE OAKLEY Program.

Recognizing that the basic high risk of the program, coupled with a short time frame, made the ability to "pre" program system designs on the developmental system very desirable. Those concepts which proved valuable were, as soon as possible, implemented as back fits to the mainstream efforts. The use of wind correction, timing of events, and use of a more flexible sorting technique were three specific items noted at the 7 September test at Eglin to be incorporated by 28 September into the mainstream effort. Concepts presently being investigated for further improvement are sensor registration and pre-sort. The latter has already proven itself, but time constraints did not permit inclusion into the 28 September demonstration. Enclosure (9) briefly describes the present developmental (25 September) system.

## TEST RESULTS

A composite sensor and system test was performed on 7 September at Eglin AFB, Florida to allow system effectiveness determination for all three computer systems. In both the airborne and ground systems, analog tape of the output of the receiving systems was made for post-analysis purposes, while at the same time the individual activation rates of the sensor were independently observed so that sensor performance could be singled out. The test plan, enclosure (10) was essentially adhered to while the test result analyses revealed that:

1. All r-f links, including the uhf link direct from the sensors to the aircraft computer system and the S-band linkage to the system via aircraft or ground station relay, behaved properly with very little loss of detection or invalid identification of sensors.
2. The sensors, both implanted and hanging, gave very little false alarm from natural environmental conditions (no adverse weather existed) and detection ranges to 11 km with a 92 percent assurance for the 105/155 artillery pieces and 85 percent for the 81-mm mortar.

REFERENCE POINT

LATITUDE 44 27 13 N

LONGITUDE 062 31 19 W

IMPULSIVE A. O.

SCALE 8 1 M  
CATEGORY U .A.

FIGURE 5 - Impulsive ANNIE OAKLEY - Display in Communication Mode

L-13



3. In a moderate sensor triggering environment, (once every 8 seconds) with reasonable good geometry, (sensors approximately surrounding the target), for sensor ranges of 1 to 3 km, grouping accuracy of 15 meters and absolute bias errors of 30 meters were readily obtained with essentially no false alarms. Figure 6, a hard-copy printout of two mortars (letter C) firing with a spacing 200 meters from each other reflect this accuracy. In general, as spacing increases the accuracy linearly decreases (i.e., at 4 km sensor spacing the accuracy would have been 30 meters grouping and 60 meters bias). By the same token with less optimum sensor geometry, the accuracy can decrease considerably. In the test, two 155-mm artillery pieces were placed near the edge of the sensor field so that centroid oriented geometry could not exist (figure 7, letters B, reflecting artillery locations). In this case grouping errors of 30 meters and 100 meters bias errors existed.

4. In a moderate sensor triggering environment (once every ten seconds), injection of random sensor location errors to 100 meters caused bias errors less than 60 meters in good geometry cases to 300 meters in bad geometry cases. Analytically, the fixing technique of the program tends to minimize location errors due to random sensor error because multiple triads (normally three, using different sensors) are used with the average tending to cause error cancellation. In general for good geometry, bias errors of less than one-half the "average" sensor error could be expected with the existing computer program. If all sensors were uniformly translated in location and not random, all fixes regardless of geometry would be transposed by the sensor error.

5. In a high sensor triggering environment (about once every 2-1/2 seconds), POD decreased to 60 percent while negligible false alarms occurred; in a controlled test, seven guns fired randomly with approximately 5 seconds spacing between firings. In addition, almost all impacts were heard by the sensor field giving a 2-1/2 second average sensor trigger rate. Figure 8 shows the grouping of the data for the three 105-mm guns about 200 meters apart from each other located with moderately good geometry. The three locations are quite evident, with the hard-copy printer validating more than one fix located at each site. One false alarm 1000 meters off also occurred. An average error of less than 100 meters existed for all guns. When random sensor errors up to 100 meters were added to each sensor, average location errors increased to 200 meters, with some false alarms occurring. Figure 9 reflects the location of three guns with sensor error; again for the rapid fire case. Under similar circumstances, the mortars with good geometry had their bias errors increased to 80 meters. In all the above cases, a flat 340 meter/second velocity with no wind correction was used.

6. In a very high firing environment (once a second), the POD dropped to about 20 percent with some increase in false alarm. At this rate, two factors greatly govern the system's performance, both leading to the system having less opportunity for detection. The first is due to an increase of overall noise level in the sensor field causing decreased detection opportunity. The second is due to the lack of a fixing opportunity of a sensor to be used for fixing due to deactivation from a previously triggered signal (up to 3/4 seconds). Post analysis of trigger rates revealed that more than one-half of all trigger opportunities per sensor were lost in this firing environment which greatly reduced system detections. In spite of this, useful locations could be identified.

0

27

C

C

Z11

Z10

IMPULSIVE A. D.

SCALE 2 KM  
CATEGORY 0

FIGURE 6 - Target Display Presentation

L-15

0

22

23

B

B

26

IMPULSIVE A. C.

SCALE 2 NM  
CATEGORY 0

FIGURE 7 - Target Display Presentation

L-16

26

25





29

IMPULSIVE A. O.

SCALE 2 KM  
CATEGORY 0

**FIGURE 8 - Target Display Presentation**

L-17

218

217                    A   A   A

221

IMPULSIVE A. D.

SCALE 2    KM  
CATEGORY 0

FIGURE 9 - Target Display Presentation

L-18

27

C

C

211

210

1

IMPULSIVE A. D.

SCALE 2 1.M  
CATEGORY 0

FIGURE 10 - Target Display Presentation

L-19

Figure 10 shows the two mortar locations determined with less than 100 meters error, even with up to 100 meters random sensor error existing when the sensors were triggered an average of one a second.

## CONCLUSIONS AND RECOMMENDATIONS

The test results of all three systems, including their appropriate r-f links, were well above the original estimates of system performance. As the operational scenario is understood today it is felt that any of the three systems could meet the operational criteria for an interim system. Also, that with continued subroutine program additions, already conceptually developed in previous Army efforts and in the developmental system, a further increase in the overall effectiveness of the system would follow. Specific areas of recommended implementation are as follows:

1. Ability of the system to monitor a large number of sensors and ultimately determine for itself which of the many areas it should be monitoring. The basic systems now require some human intervention to determine areas of sensors to be used for particular areas of coverage. This software modification is conceptually a minor one requiring a sub-routine which would note logical groupings of sensors for any particular area and then predetermining whether sufficient activation exists on those sensors to merit them being a part of the gun location routine.

2. A better soft-copy display capability is required for the ground based system. Mainly due to cost, availability and time constraints, only a diminutive form of what is considered the idealized soft-copy display system could be demonstrated for the ground based system. The display system with a "hook" function and resolution of the airborne P3C aircraft is considered to be most adequate for any operational system, and it should be made part of the ground based system.

3. Other previously proven subroutines, such as mini-sort, watch point, sensor registration and auto wind determination, should be added to the computer's program to improve overall computer system performance.

4. Add the ability to store from all input sensors the time of arrivals on digital tape in order to allow post-analysis investigation from sensor/sensor combinations which were not investigated in the real time mode.

5. Possibly the most single major important improvement that should be made to the overall system is an improved version of the sensor which would allow in a digital format information related to classification of the signal heard. The problem of the ability of finding guns which have been masked by a high impact rate, as previously mentioned for SEA scenerio, could be overcome by such a sensor. Previous studies for the Army reveal that such things are possible, at least partially, but that a development program of at least six to nine months would be required for this major modification of the sensor.

In summary, it is felt that the ground based system is operational today if the requirement still exists, and that the airborne system with some software improvements could also be used as a valuable alternative if a suitable ground based location did not exist. In any event, based upon the fairly impressive results that have been demonstrated during a rather difficult test environment, as compared to previous efforts that have been done for various sound ranging systems in the Army, it is recommended that continuing development work for army needs be pursued to exploit the results of this emergency funding program.

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- (f) The Johns Hopkins University/Applied Physics Laboratory SECRET Report No. TG-1162-A of Jun 1971, "DAALS System Synthesis Final Report, Vol 1" (U).
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- (h) The Johns Hopkins University/Applied Physics Laboratory SECRET Report No. TG-1162-C of Nov 1971, "DAALS System Synthesis Final Report Vol. 3" (U) (Appendixes).
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